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A VULNERABILITY EVALUATION OF EMULSIFIED FUELS FOR USE IN ARMY AIRCRAFT

By

George H. Custard

April 1968

U. S. ARMY AVIATION MATERIEL LABORATORIES
FORT EUSTIS, VIRGINIA

CONTRACT DA 44-177-AMC-415(T)

FALCON RESEARCH AND DEVELOPMENT COMPANY
DENVER, COLORADO

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Falcon Research and Development Company
Denver, Colorado

April 1968

DEPARTMENT OF THE ARMY
U. S. ARMY AVIATION MATERIEL LABORATORIES
FORT EUSTIS, VIRGINIA 23604

This report was prepared by Falcon Research and Development Company, Denver, Colorado, under the terms of Contract DA 44-177-AMC-415(T). It consists of an evaluation of the properties of emulsified fuels which were felt to be related to crash conditions and small-arms ballistic attack.

The evaluation of the results shows that emulsified fuels have properties which would be expected to contribute significantly to the reduction of losses of Army aircraft from both post-crash fire and small-arms attack. A direct comparison of the results of these experiments and actual field conditions is impossible because no two crashes or small-arms attacks occur under the same conditions. These experiments were designed to evaluate general properties which were felt to be related to the overall safety criteria associated with aircraft fuel. Only by full-scale usage can the exact safety advantages be determined.

It should be pointed out that the emulsified fuels used in these tests were not made from the same base JP-4 stocks, that they were not manufactured in the same manner, and that they were evaluated at different ages and physical conditions. Thus, detailed comparisons should not be made of specific emulsions; rather, the results should be evaluated as to the general performance of emulsions as compared to JP-4.

The conclusions and recommendations contained herein are concurred in by this Command. However, this concurrence does not imply that this Command feels that this report completely evaluates the relative advantages of JP-4 and emulsified fuels. Additional testing of a more definitive nature is needed to establish more reliable comparisons of different emulsified fuels and liquid JP-4.

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For

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SUMMARY

This evaluation of emulsified JP-4 has concentrated upon the fuel properties which relate to the ignition and propagation of fire under the conditions of ballistic attack and survivable aircraft accidents. The specific areas of study and testing include the following:

1. Fuel combustion rates as a function of air velocity and air temperature.
2. Fuel vaporization rates under closed-tank and vented-tank conditions.
3. Fuel permeability.
4. Fuel dispersion characteristics under conditions of high-velocity ballistic impact and spillage from heights of up to 20 feet.
5. Ease of fuel droplet or spray ignition with various energy sources.
6. Fuel and tank panel behavior when hit by functioned incendiary bullets.
7. Fire extinguishing ease with a variety of extinguishants against a standardized fire.
8. Self-sealing panel performance with fuel emulsions.

The fuels tested included liquid JP-4 and three JP-4 emulsions. These emulsions were designated MEF, EF4-104, and WSX-7165 and were developed by Monsanto Research Corporation, Petrolite Corporation, and Esso Research and Engineering Company, respectively. All but the Petrolite product were developed under U. S. Army sponsorship. The ballistic firing tests employed caliber .30, caliber .50, and 20 mm ammunition sizes and involved fuel tank material responses with conventional self-sealing panels, crash-resistant panels, and coagulant-sealing tank panels.

The WSX-7165 fuel was shown to burn more slowly than liquid JP-4 or the other emulsions tested when the air velocity across the fire was higher than about 20 feet per second. At lower air velocities, all fuels burned at similar rates per unit of fire surface.

The emulsified fuels vaporize much more slowly at 70°F than liquid JP-4. MEF and EF4-104 emulsions took nearly ten times as long to form an explosive fuel-air mixture as did the liquid fuel, and the WSX-7165 took 100 times as long.

The fuel dispersion characteristics of the emulsions were not greatly different from those of liquid JP-4 under the high-velocity impact conditions of the tests. The emulsified fuels did cohere somewhat longer, to form larger fuel droplets and to maintain slightly narrower dispersion patterns.

The regions of most probable ignition were smaller for the emulsified fuels than for liquid JP-4 with both electric spark and hot-metal surface ignitors. Fuel ignitions were accomplished with all ignitors and all fuels under the more favorable conditions.

Tests with incendiary ammunition showed that fuel fires can be started by incendiary rounds functioned outside of all types of tank material in combination with all of the types of fuel tested. The fires produced with emulsified fuels were generally smaller and more easily extinguished than similar fires with liquid JP-4.

Water fog, sand, water, and air were able to extinguish emulsified fuel fires faster and with less extinguishant than was required for similar liquid JP-4 fires. Dry chemical, CO_2, and liquid foam extinguishants were equally effective against all fires.

The emulsified fuels were found to react well with conventional self-sealing tank materials and were much more apt to be retained in a severely damaged tank than liquid JP-4.

The emulsified fuels were prepared from different batches of JP-4 and were prepared by different processing methods, thus care should be exercised in making direct comparisons of these JP-4 emulsions.

It has been concluded from this study that emulsified fuels offer opportunities for greater aircraft survivability from several standpoints, but that they may be employed most advantageously as a part of a total passive defense system for aircraft fuel.

FOREWORD

The work summarized in this report was conducted under Contract DA 44-177-AMC-415(T) during the period 1 January 1967 to 31 December 1967. Technical direction for the project was provided by the following USAAVLABS personnel: Mr. Francis P. McCourt, Chief, Safety and Survivability Division; Mr. William J. Nolan, Project Engineer; Mr. James T. Robinson, head of the Aircraft Vulnerability Section; and Captain George W. Bowling, Assistant Project Engineer.

The study was conducted by the Falcon Research and Development Company under the guidance of Mr. Arthur M. Krill, President. Mr. George H. Custard served as Project Supervisor and was ably assisted by Mr. Gale S. Weeding and Mr. James McFadden. Other persons assisting in the project at the Falcon Research and Development Company include Mr. Charles E. Eppinger, Mr. Donald Saum, Mr. Harold Windle, Mr. Melvin West, and Mrs. Jerry Foster.

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I. INTRODUCTION

Thickened or solidified fuels for use in aircraft have received intensive study during the past five years. Initially, gels were developed and tested for this purpose; more recently, a variety of fuel emulsions have been formulated and subjected to testing in aircraft fuel system components.

The objective of this continuing effort to adapt thickened fuels to aircraft has been a major reduction in the loss of life and property which is associated with crash fires and with combat fires resulting from enemy action. It is clear that many aircraft and many human lives are continuing to be lost in fires following aircraft crashes which would have been survivable from the standpoint of the impact forces alone. Liquid fuels run out of damaged fuel lines and tanks and form large pools of fire under and around the aircraft. Similar leakage of fuel and spreading of fire take place within aircraft structure following bullet perforations of fuel systems. Solid fuels would resist this disastrous spreading of fire to the extent that they resist flow from damaged components. The candidate solidified fuels may also be of value in reducing the probability of fire ignition, reducing fire intensity, or increasing the ease of fire extinguishment.

This program has sought to evaluate these latter aspects of the emulsified fuels included in the study. The flow properties and apparent viscosity of the fuels have been investigated by the fuel developers and by organizations such as the U. S. Army Fuels and Lubricants Laboratory. Thus, fuel rheology, important as it is to every aspect of fuel use and safety, was not under direct study in this program.

This effort has included an investigation of the rate at which candidate fuels are consumed, in a constant area fire, under varying wind conditions. The rates at which vapors escape from the fuel surface and form explosive mixtures with air have been determined. Also, other technical areas such as the fuel dispersion patterns which result from high-velocity bullet impacts and fuel spillage from heights up to 20 feet have been studied. The fuel ignition susceptibility of these fuel or droplet patterns with electric sparks,

hot-metal surfaces, and incendiary ammunition bursts has been measured. Finally, the project personnel have completed a series of extinguishing tests that provided quantitative data relative to the fire extinguishment susceptibility of emulsified fuel fires to a variety of extinguishing agents.

A related effort has considered the action of emulsified fuels upon conventional self-sealing fuel cell construction, upon crash-resistant panels which have no sealing layer, and upon self-sealing materials which provide a coagulant layer to achieve wound closure.

It is hoped that the information which is provided will be useful in judging the merits of the fuel emulsions studied and that the reported data will offer guidance for the development of even more advanced fuels in the continuing search for safer sources of energy for aircraft.

II. FUEL-BURNING RATE EVALUATION

A. DISCUSSION OF THE TEST SERIES

The intensity of a fire is largely determined by the rate at which fuel is vaporized and reacted with oxidizer. This series of tests was designed to determine the potential fire intensity of the fuels of interest as a function of air velocity and air temperature. The data will be presented in units of fuel consumed per minute. The grams per minute may be converted directly to heat released by multiplying by 40 BTU per gram.

The arrangement of the test equipment was as shown in Figure 1.

Test Plan No. 3, to be found in Appendix II, presents the detailed procedures used in the tests. The most significant factors are as follows:

1. The burning of the fuel was continuous from ignition to extinction.

2. One thousand grams of fuel were burned in an 8- by 8-inch pan for each test run.

3. Time was recorded to the closest second from fuel ignition to the time of consumption of each 100-gram increment of fuel.

Figure 2 shows the appearance of the pan of burning fuel for typical runs. Note that the flame is quite laminar but that it spreads out from the sides of the pan as well as directly downwind. Note also that there is little or no flame along the upwind edge of the pan.

Liquid fuel tended to "pile up" along the downwind edge of the pan at high airflow rates, but the emulsified fuels did not present this problem. The emulsions were more likely to burn rapidly along the downwind side of the pan and leave a mound of burning fuel on the upwind side of the pan during the latter stages of a burn test. With the MEF and EF4-104 emulsions, sufficient liquid fuel was produced by the heat of the fire to maintain the 64-square-inch fire surface

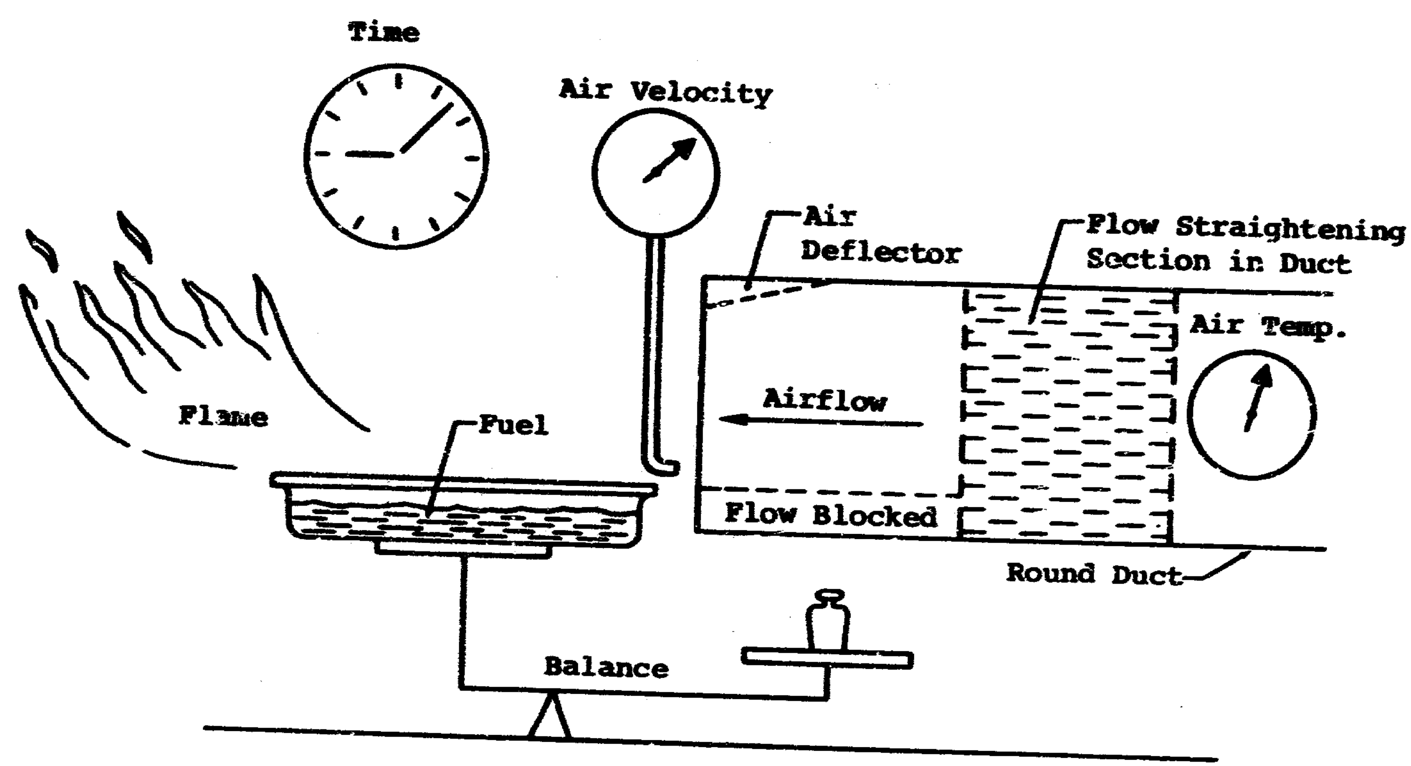


Figure 1. Arrangement of Test Equipment for Fuel Burning Rate Evaluation.

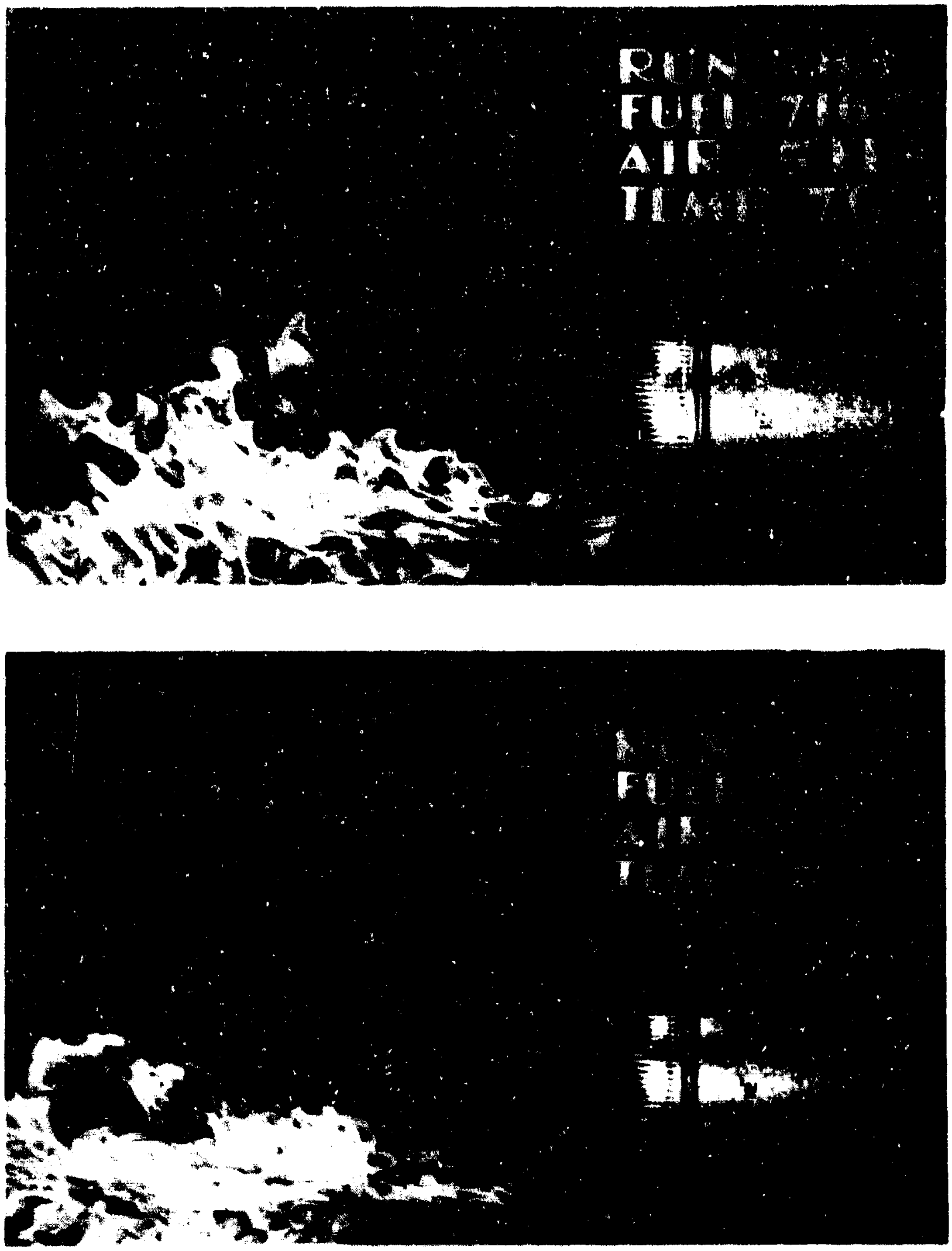


Figure 2. The Appearance of Fuel Burning in the Combustion Rate Test at Two Air Rates.

throughout most of the test run. With the burning WSX-7165 fuel, very little liquid was liberated from the emulsion by the heat of the fire. Thus, this fuel actually burned the pan dry on the downwind side, toward the end of the run, while a substantial lump of fuel continued to burn on the upwind side of the pan. In this case, the burning surface area was reduced late in the run.

B. THE EFFECT OF AIR VELOCITY ON BURNING RATE

The effect of air velocity on burning rate was determined by running tests at 5, 15, and 25 feet per second while holding the temperature constant at about 70°F. At least two runs were completed at each condition. Thus, the data presented in Figures 3 through 6 are an average of the values from two or more runs. Burn rates are plotted at the midpoint of each time interval. Thus, the distance (in time units) between plotted points varies as the burning rate varies.

Generally, the burning rates were quite reproducible, and the averaged values were often very close together. It is believed that the data presented accurately represent the rates at which fuel is consumed under the test conditions and that even the apparent irregularities in the curves are significant. Each curve may be thought of in terms of three separate regions. First, there is an ignition and rapid heating period during which the fuel and its environment are changing temperatures rapidly. This lasts from 1 to 3 minutes while the first 10 to 15 percent of the fuel is being consumed. This period is followed by a relatively straight and often flat portion of the curve where the burning rate is constant or is increasing gradually as the fuel mass continues to be heated by the flame. About 70 percent of the fuel is consumed during this portion of the cycle. Finally, toward the end of the burn, the mass of the burn pan exceeds the mass of the remaining fuel and thus the heat transfer characteristics of the fuel container may become a dominant factor in the determination of the fuel-burning rate. This final phase of the cycle consumes the last 10 or 15 percent of the fuel and may be the least significant portion of the plots which are presented.

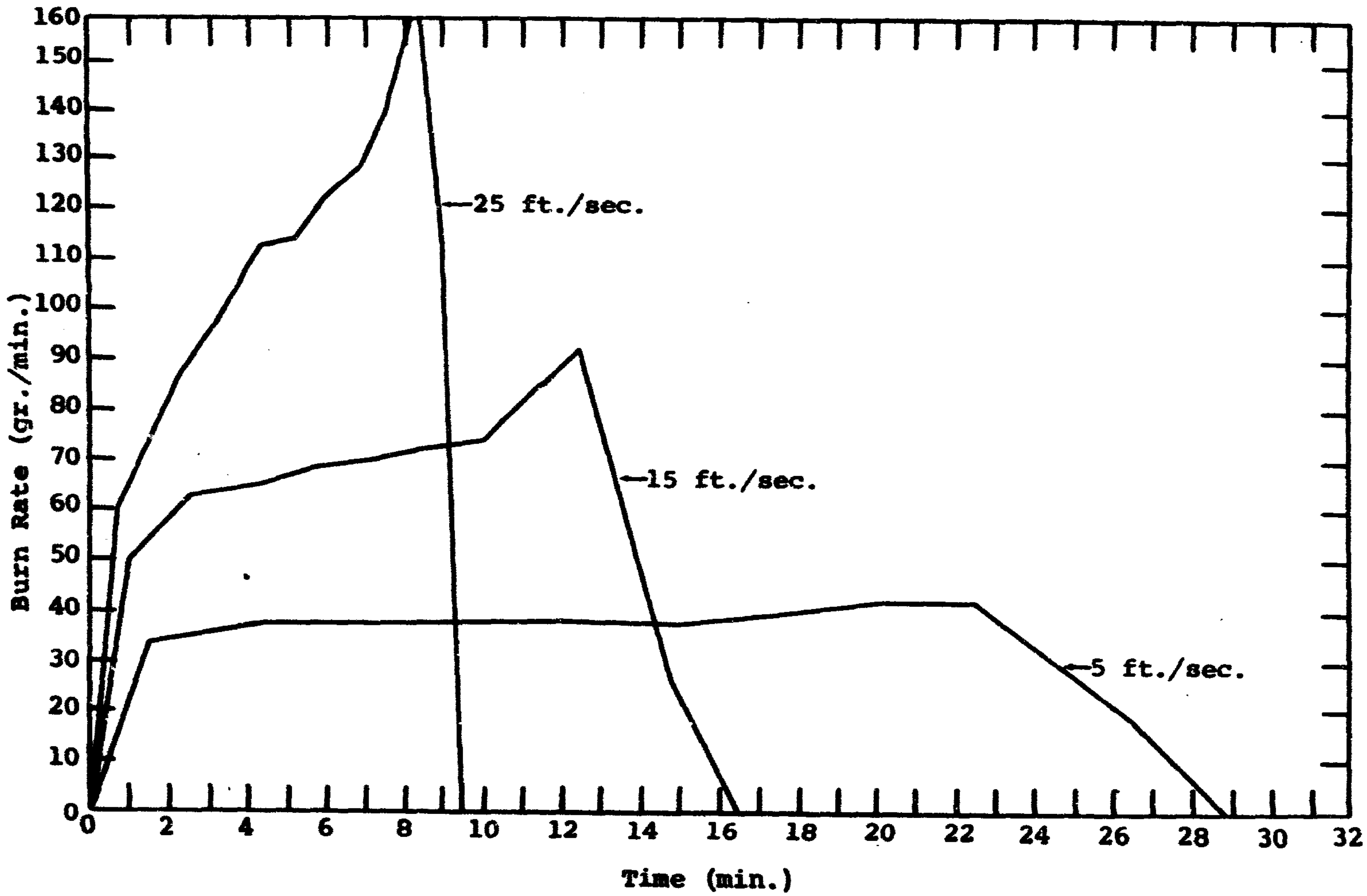


Figure 3. JP-4 Burning Rates as a Function of Air Velocity and Time (64 $in.^2$ surface and 70°F air temperature).

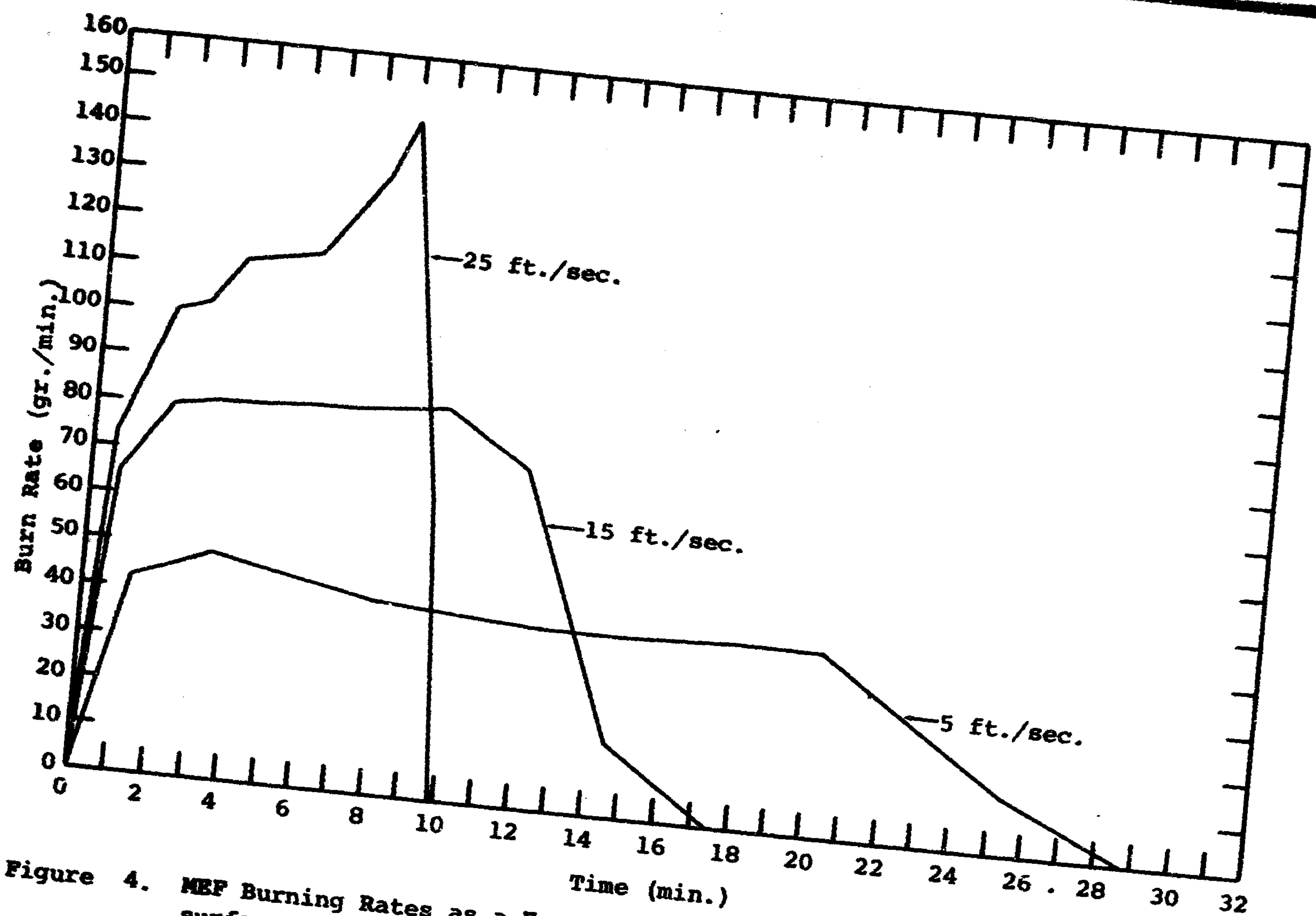


Figure 4. MEF Burning Rates as a Function of Air Velocity and Time (64 in.2 surface and 70°F air temperature).

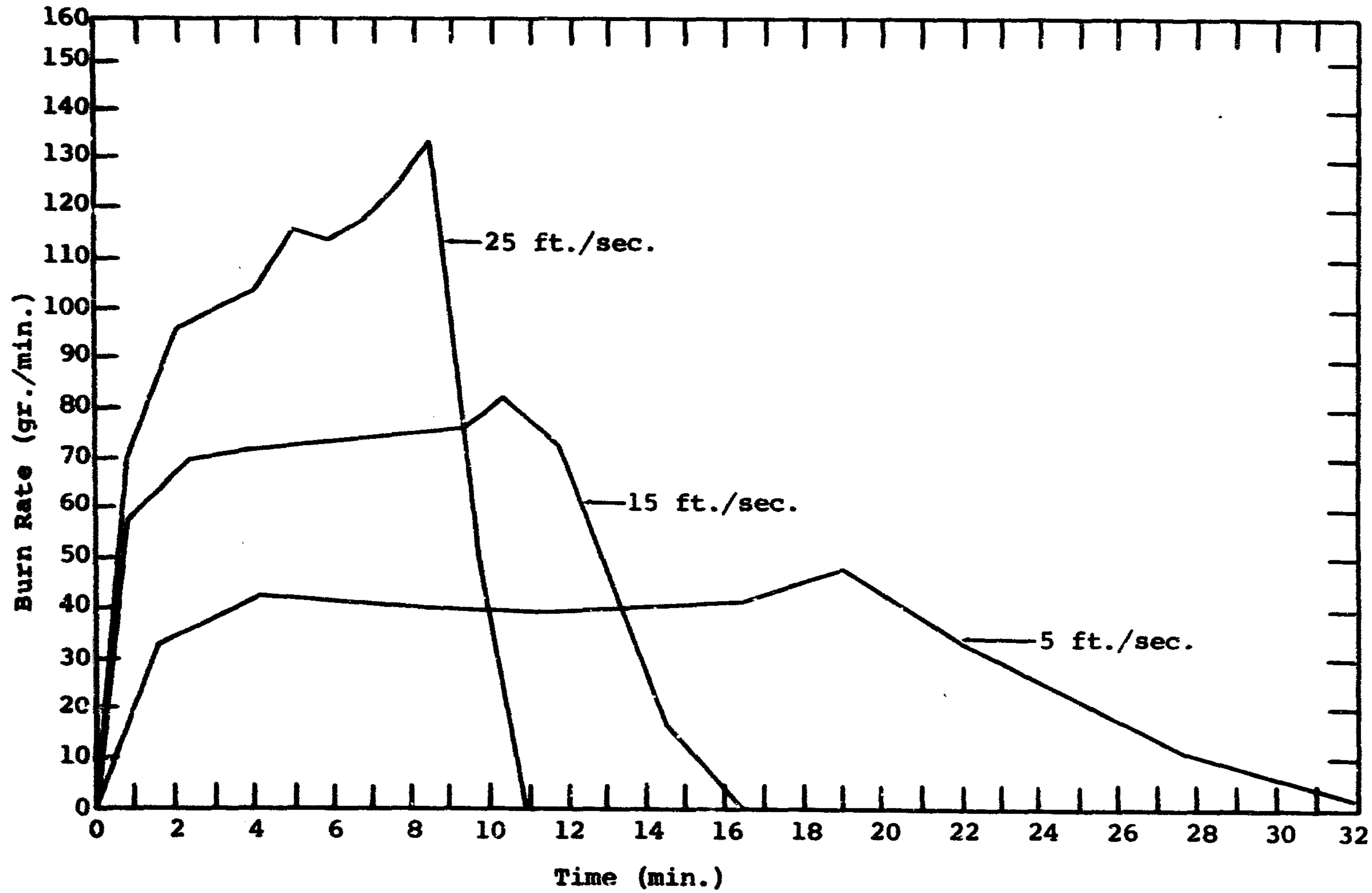


Figure 5. EF4-104 Burning Rates as a Function of Air Velocity and Time (64 in.^{2} surface and 70°F air temperature).

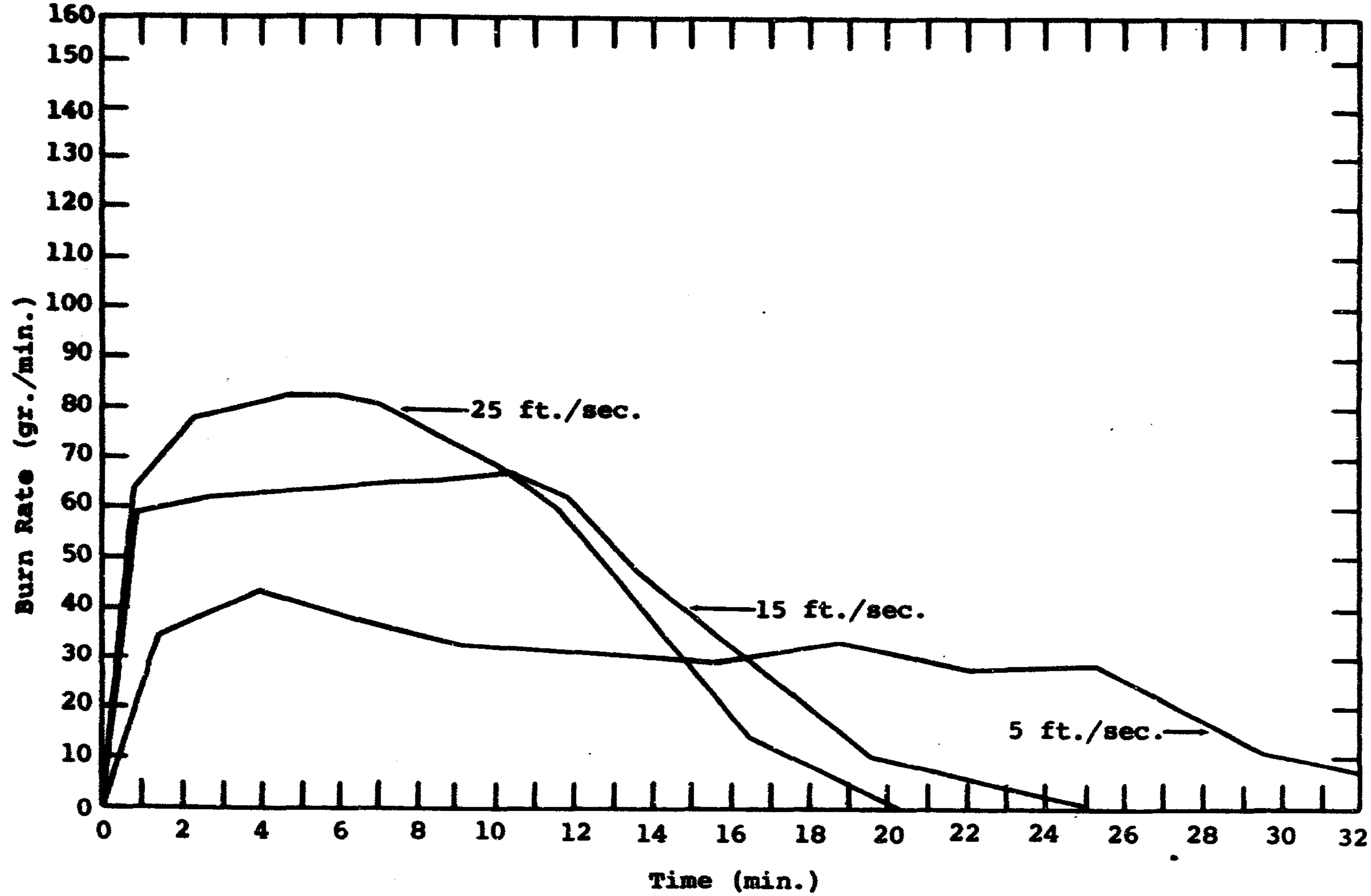


Figure 6. WSX-7165 Burning Rates as a Function of Air Velocity and Time (64 $in.^2$ surface and 70°F air temperature).

The central region of the plot is the most significant, and thus the most relevant comparisons between fuels and burn conditions can be made in this portion of the curve. An examination of these data quickly reveals two significant points. First, the burning rate is influenced greatly by the velocity of the airstream across the fuel. Second, all fuels burn at similar rates under similar test conditions with the single exception of the WSX-7165 emulsion at the highest air rate. This emulsion burned at a somewhat lower rate than the other fuels under each airflow condition, but the difference really becomes dramatic at the air rate of 25 feet per second. The peak burning rate for the WSX-7165 fuel is little more than half the peak rates determined for the other fuels under this wind condition. This is a 15-knot wind and may surely be expected to be present in the crash environment of some aircraft fires.

The reduction in burning rate for the WSX-7165 emulsion seems to be the result of the very great thermal stability of this fuel. The other emulsions were partially broken by the heat of the fire so that a significant quantity of liquid fuel was always present in the pan. The WSX-7165 burned from the emulsion surface with very little, if any, liquid fuel apparent. Thus, the controlling rate process for the vaporization of fuel may be expected to be quite different for the WSX-7165 fuel.

At the lower air velocities, the differences between the burning rates for the four fuels are slight, although they are greater than experimental variation and are thus statistically significant. A burning rate of 40 grams per minute (± 15%) at an air velocity of 5 feet per second would satisfactorily approximate the burning of all fuels at this air rate. Similarly, a value of 70 grams per minute (± 15%) would cover all fuels at 15 feet per second. Expressed in other terms, all fuels tested may be expected to release 3,000 to 4,000 BTU's per minute per square foot of burning fuel surface in a 3-knot wind. The heat release will increase to 6,000 to 7,000 BTU's per minute per square foot of fuel surface in a 9-knot wind and will exceed 10,000 BTU's per minute per square foot of fuel surface in a 15-knot wind if the emulsified fuel is partially broken by the heat of the fire.

C. THE EFFECT OF AIR TEMPERATURE ON BURNING RATE

A second aspect of the fuel-burning rate study provided data relative to the effect of air temperature on fuel-burning rates. Tests were conducted at 40°F, 70°F, and 110°F (± 5°F) for each fuel. For these tests, the air velocity was held constant at 15 feet per second. Figures 7 through 10 present the results of these tests. Each plotted line represents an average of at least two runs.

An examination of these data clearly indicates that fuel burning rate is not dependent upon air temperature to any significant extent. The slight differences between runs is to be attributed to slight variations in air velocity rather than to any other factor. It should be noted that exhaust ventilation supplied a major portion of the motive forces used to move the controlled airstream. The air velocity was thus somewhat affected by wind conditions outside the building, and it was not possible to control this parameter more closely than about ± 5 percent.

D. CONCLUSIONS

In summary, the work conducted under this phase of the program has shown that fuel burning rates are highly dependent upon air velocity and are independent of air temperature. The MEF and EF4-104 fuel emulsions burned at rates which were very close to the burning rates for liquid JP-4 under the same conditions, although the peak burning rates in any run generally were lower for emulsions than for liquid JP-4 fuel. The WSX-7165 fuel burned at slightly lower rates than any other fuel under the lower air velocity conditions and at a much lower rate at the 25-feet-per-second wind condition. It must be concluded that emulsified fuels provide only a marginal safety advantage over liquid fuels when judged only by the single criterion of fuel-burning rate per unit of fire surface. Their advantage in this respect is greatest when the emulsions are very stable in the fire environment.

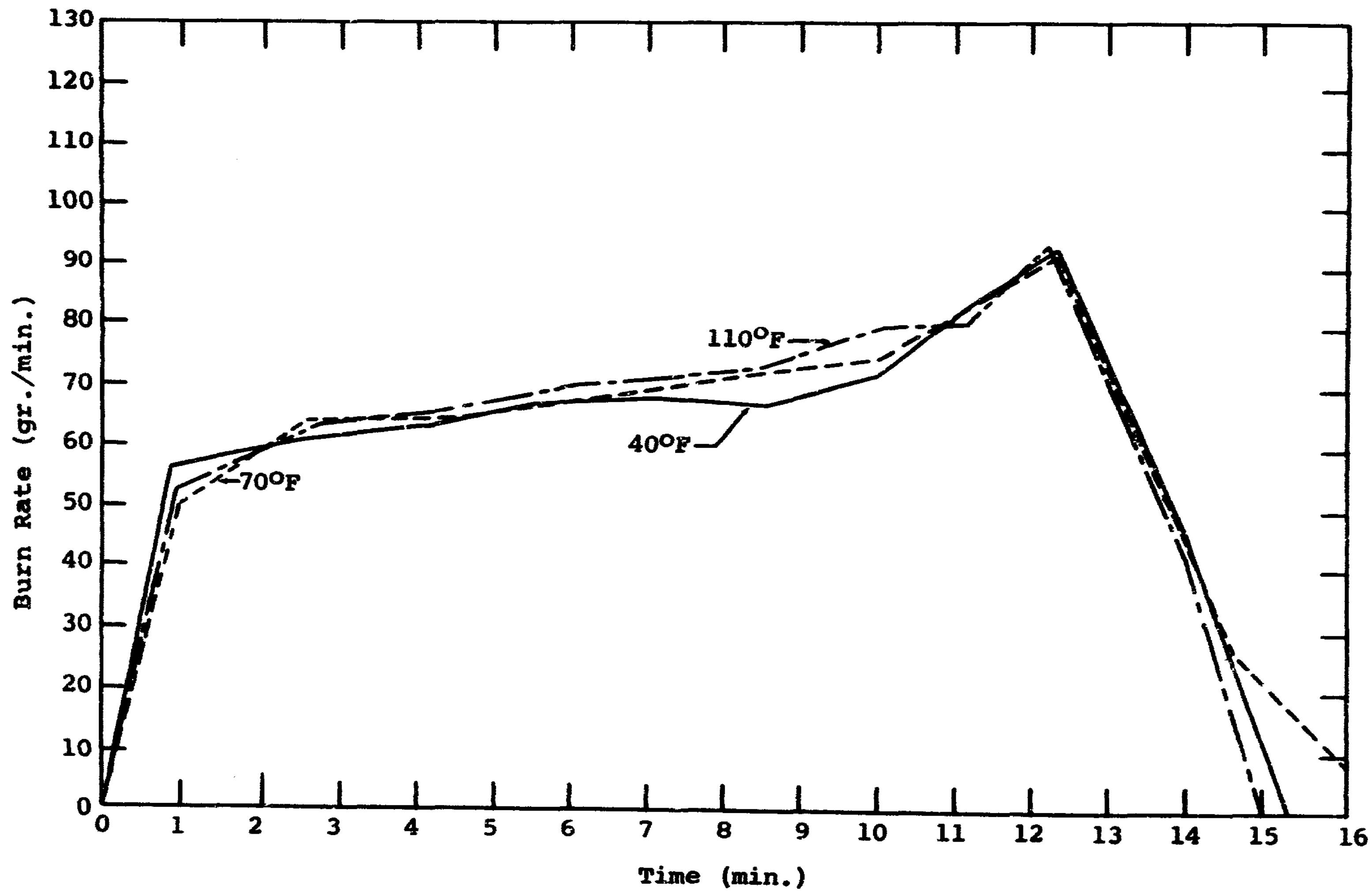


Figure 7. JP-4 Burning Rates as a Function of Temperature and Time (64 in.^{2} surface and 15 ft./sec. air velocity).

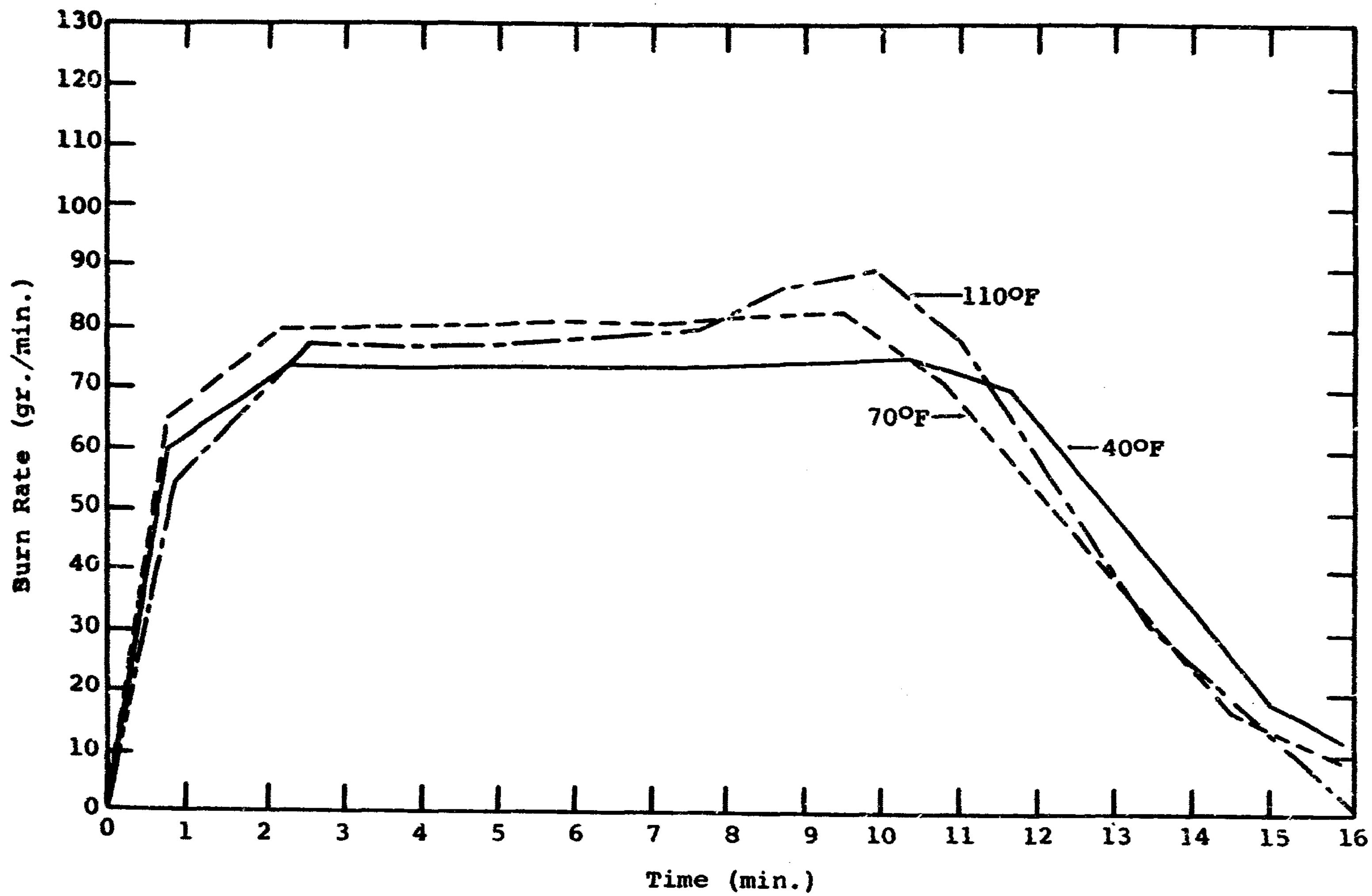


Figure 8. MEF Fuel Emulsion Burning Rates as a Function of Temperature and Time (64 in.^{2} surface and 15 ft./sec. air velocity).

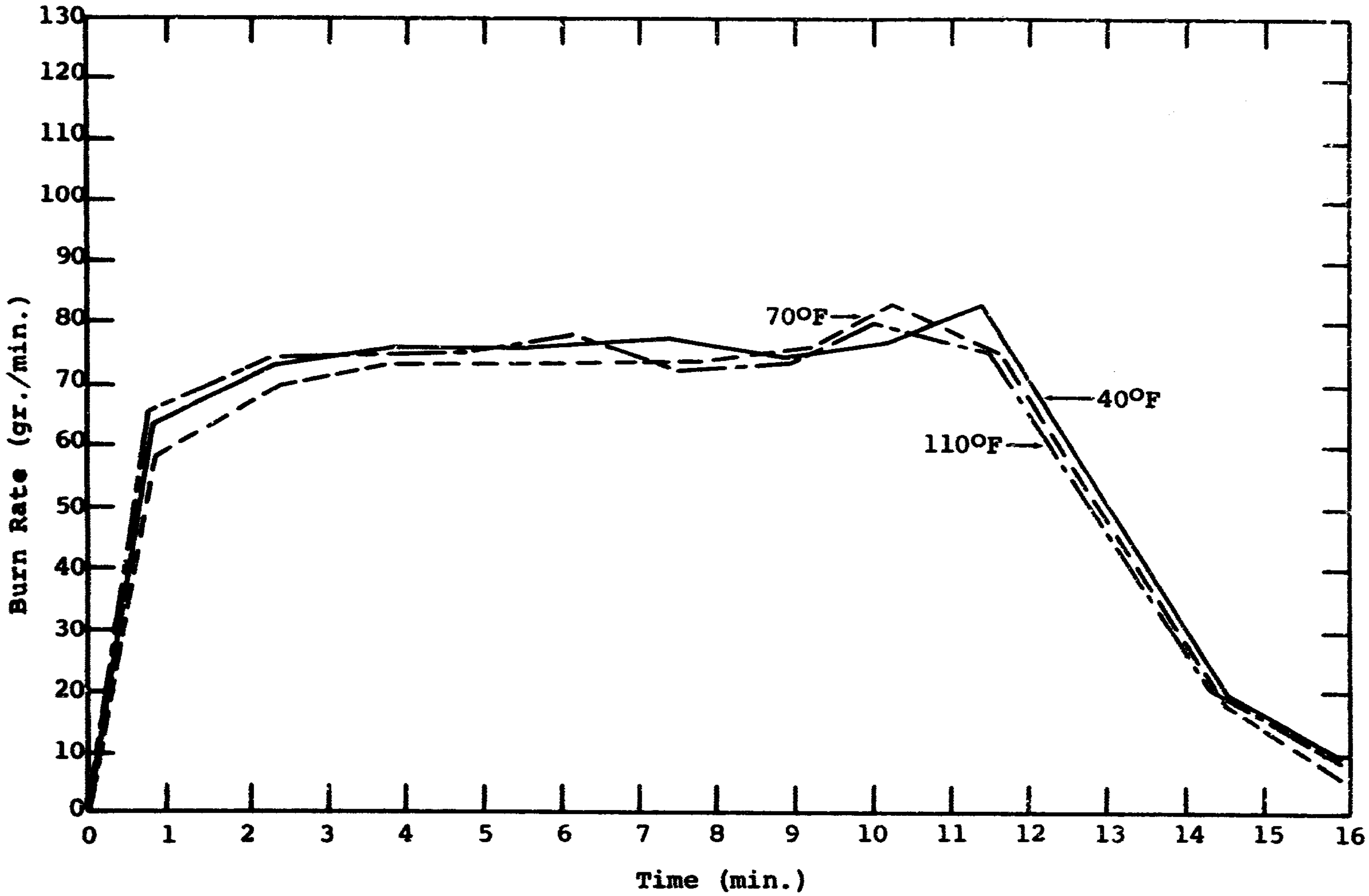


Figure 9. EF4-104 Fuel Emulsion Burning Rates as a Function of Temperature and Time (64 in.^{2} surface and 15 ft./sec. air velocity).

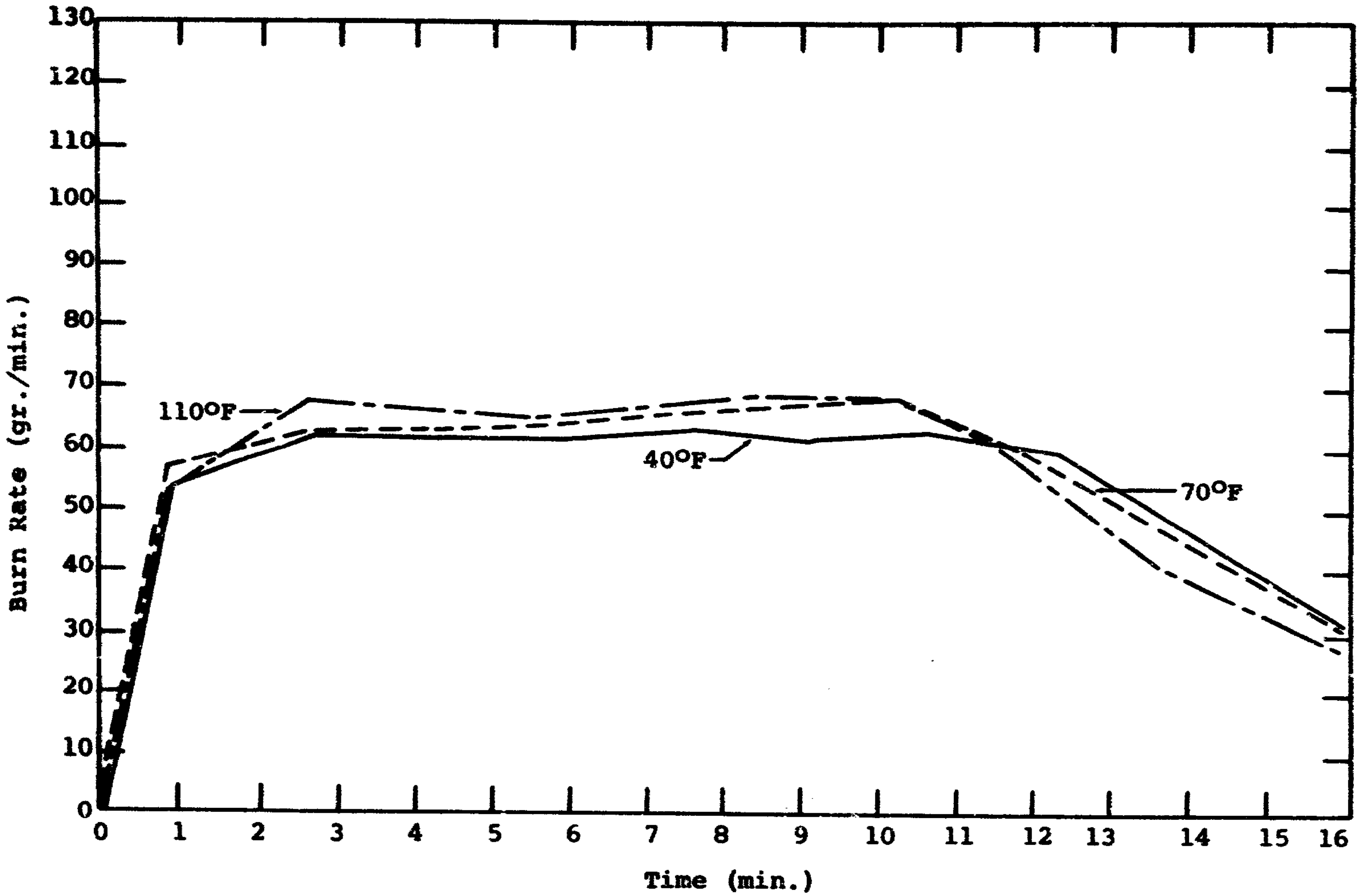


Figure 10. WSX-7165 Fuel Emulsion Burning Rates as a Function of Temperature and Time (64 in.^{2} surface and 15 ft./sec. air velocity).

III. FUEL VAPORIZATION STUDY

A. DISCUSSION OF THE TESTS

Aircraft fuel tanks are generally vented to the atmosphere, and thus they contain air in the space above the fuel. Vapors from this fuel also escape into this space and become mixed with the air through convection. Initially, the fuel-air mixture may contain only a very small percentage of fuel vapor, and thus it will not propagate an explosion. Such mixtures are referred to as "lean". As time goes on, more and more fuel vapor is added to the mixture. This vaporization process is dependent upon the temperature and pressure under which the action is taking place and upon the molecular composition of the fuel. The vaporization process can also be affected by mechanical barriers such as the external phase of an emulsion or a layer of plastic film.

As the fuel vaporization process continues, a point may eventually be reached at which the mixture of fuel and air molecules will propagate a flame front. This is generally referred to as the "lean explosive limit" or simply as the "lean limit". Explosions of aircraft fuel vapors near this limit are characterized by a very blue flame. As vaporization of fuel continues, the strength of the explosive wave will increase and the color of the flame will move toward a white or yellow white. If vaporization of fuel continues long enough, the ideal (stoichiometric) mixture of fuel vapor and air will be passed; from this point on, additional quantities of fuel will weaken the explosive wave and will cause the color of the flame to become more red or orange. Finally, a fuel-air mixture can be reached where there are so many fuel molecules in the mixture that a flame will not propagate. Fuel-air mixtures which are near this composition are referred to as being near the "rich limit". Mixtures which contain more fuel vapor than this will not propagate a flame front.

One way of understanding these explosive limits is to consider a single fuel molecule reacting with the surrounding oxygen molecules. A fuel molecule contains many atoms of carbon and hydrogen which are capable of reacting with atoms of oxygen when collisions occur. The reactions release chemical energy but will occur only if the colliding molecules

are sufficiently activated (hot enough). As the energy of reaction is released, it raises the activation or temperature of the reaction product molecules; raises the temperature of molecules of fuel, oxygen, and nitrogen which are near the point of reaction; and radiates energy in the form of light and heat to distant surfaces. If the net effect of this total process provides activated adjacent fuel and oxygen molecules which can react, and maintains them in this activated state until they collide and do react, the process is self-propagating and the reaction proceeds to the extent of available mixture. If the net effect of the initial reaction cannot provide enough energy to heat all of the adjacent molecules to the required level and maintain them there until the required collisions occur, a net cooling takes place and the flame will not propagate. This explanation may be a slight oversimplification, but it should help to show that "lean" mixtures fail to propagate an explosion because too many nitrogen molecules must be heated before the next fuel-oxygen collision occurs and that "rich" mixtures fail because too many fuel molecules must be heated before the next fuel-oxygen collision takes place.

Vapor space explosions in aircraft can be very destructive and thus it is desirable to eliminate or retard their formation. This potential of the candidate fuels was evaluated in the series of tests performed.

The tests were conducted in an explosive chamber as shown in Figure 11. Three different types of tests were performed with each fuel as described in Test Plan Number 4, which is given in Appendix II. The three types of tests can be differentiated as follows.

1. Open fuel in a sealed chamber.

2. Open fuel in a precisely vented chamber.

3. Enclosed fuel in a sealed chamber.

The minimum time required to reach the "lean limit" was determined in the first and third types of tests. The minimum vent airflow rate needed to prevent the formation of an explosive mixture was determined in the other test series.

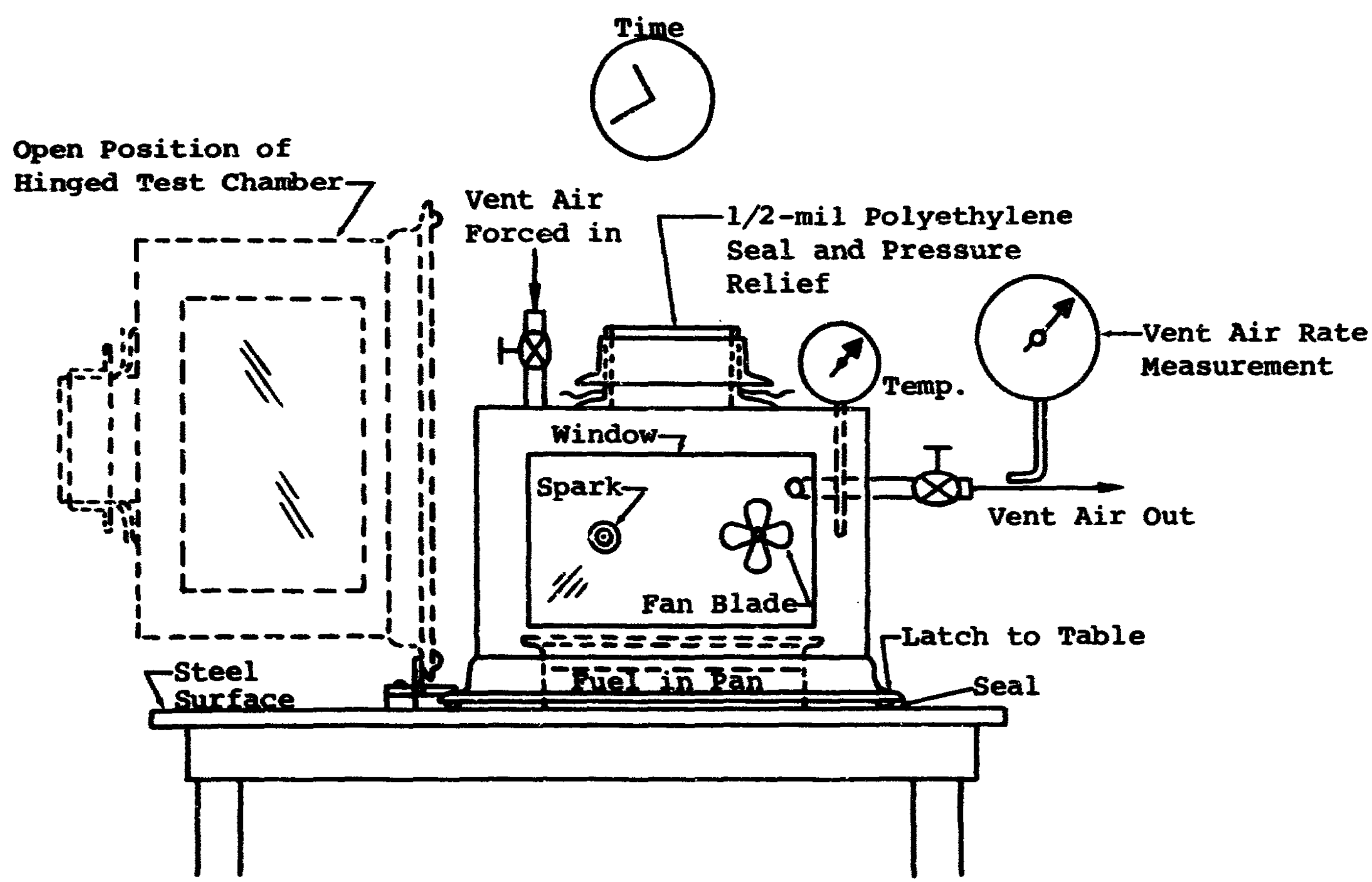


Figure 11. Explosive Vapor Chamber Used for Tests of Fuel Vaporization Rates With and Without a Vent Airstream.

The vaporization properties of the four batches of JP-4 which were used in the tests, either as liquid fuel or as emulsified fuel, have a direct bearing on these tests. All fuels met the requirements of Specification MIL-T-5624G, but this specification permits considerable latitude in the distillation characteristics of the fuel. The distillation requirements of the specification ask only that 20 percent of the fuel be distilled off at temperatures below 290°F; 50 percent, below 370°F; and 90 percent, below 470°F. Some other constraints are placed upon the distillation properties indirectly by other specification requirements, such as specific gravity, percent aromatics, smoke point, and Reid vapor pressure, but the three temperature maximums are the only direct requirement.

The inspection report for each batch of JP-4 has been provided; these reports are given in Appendix I. The distillation curves for these fuels have been extracted from the inspection reports and are plotted in Figure 12. It is clear that there are significant differences in the fuels used. The magnitude of the effect of these differences upon the results of these tests is not clear, but it is believed to be small. Note that the JP-4 used to formulate the MEF and EF4-104 emulsions actually had more of the light ends than the liquid JP-4 had. The WSX-7165 had substantially less of the low boiling fraction than any of the other fuels, but it is doubtful if even this great a change in composition could account for a tenfold change in vaporization rate, as was noted. In order to make clear definitive comparisons of the vaporization rates of the emulsified fuels, it would be necessary to make samples of all three fuels from the same JP-4 using a closed manufacturing system.

Fresh fuel was used for each test. It was measured into a separate container just prior to each test and then placed into the test container and leveled just as the test was started. While it was not possible to do this quite instantaneously, it never required more than 10 or 15 seconds, and it is believed that the reproducibility of this procedure was sufficient for the purposes of these tests.

A small fan blade was turned by a sealed shaft extending through the wall of the explosion chamber. This stirring action kept the fuel-air mixture essentially homogeneous at all times. While this condition is not representative

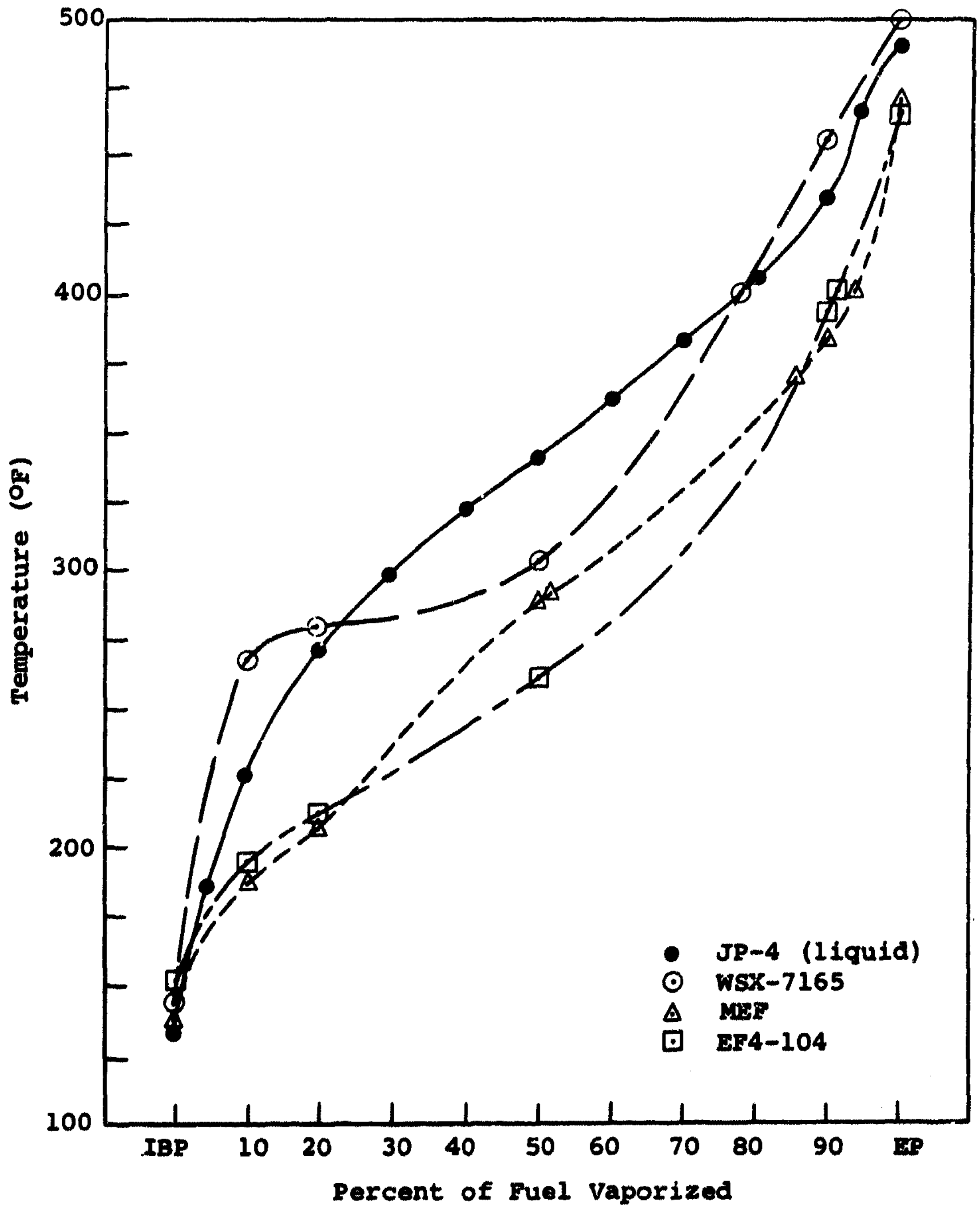


Figure 12. Distillation Curves for the Liquid JP-4 Fuel Used in This Test Program and for the JP-4 Used to Formulate the Emulsions.

of conditions within an aircraft tank, it was necessary to achieve acceptable uniformity in the test results. It was used with both the sealed chamber tests and the tests involving a flow of venting air.

Explosions were initiated by a high-voltage spark. The spark was introduced into the chamber by an automotive spark plug. The appropriate coil and condenser were used to generate the energy pulse, and a relay was used to provide the action of the distributor points. Good sparks were produced in this way. It should be noted, however, that a spark is not a very precise phenomenon in itself. The ionization path varies considerably from one spark to the next and does not necessarily follow the shortest distance between the conductors. This type of spark was very satisfactory for the tests which were accomplished. It is probable, however, that some variation in results was due to variations in sparks from one trial to the next.

The explosions always had sufficient force to blow the 4-inch pressure relief disc, and a flame passage was always witnessed visually. Often the fuel surface was briefly ignited by the explosion. Such fires went out within a very few seconds because of a lack of air in the chamber. Whenever fuel was spilled by the explosion, it was cleaned up with a soap and water solution and the chamber was dried and aired before a subsequent test.

The fuel surface area was 8 by 8 inches, and the volume of the chamber was 0.75 cubic foot. Tests were performed under ambient pressure (5,000-foot altitude) and a nominal temperature of 75°F.

B. EXPLOSIVE VAPOR FORMATION RATES FOR OPEN FUEL IN A SEALED CHAMBER

This condition helps to explain the condition within an aircraft fuel tank and may be used as a guide in considering the hazards associated with vapor space explosions in fuel tanks.

Figure 13 presents the results of this test series with the four fuels. These data were generally reproducible within

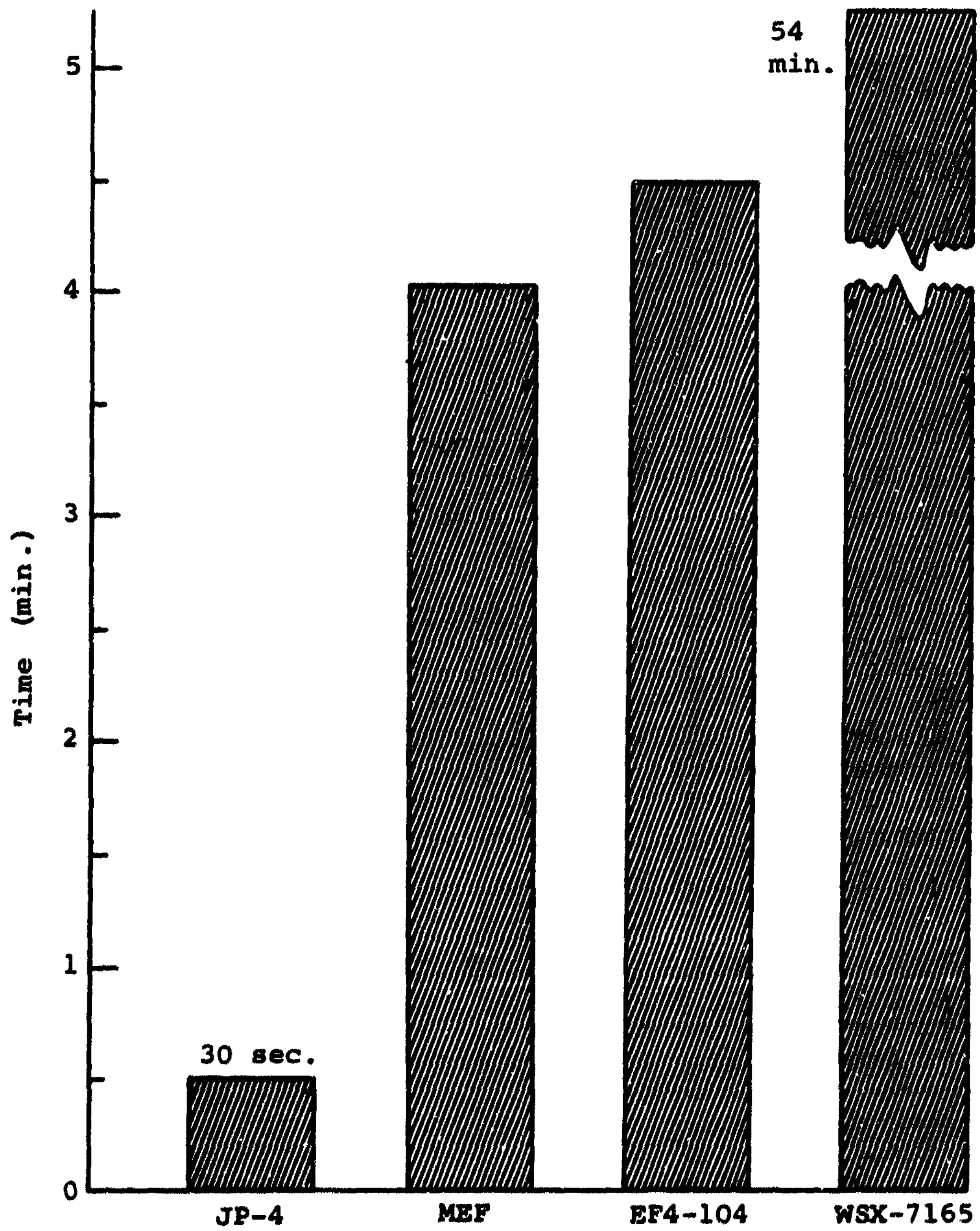


Figure 13. Time to Reach a Lean Explosive Mixture in the Test Tank Vapor Space.

± 15 percent of the time values, and each value was substantiated by at least two successes and two failures within these limits.

There is nearly a tenfold decrease in the vaporization rate of the MEF and EF4-104 emulsions when they are compared with liquid JP-4. There is a further tenfold decrease in vaporization rate between these emulsions and the WSX-7165 emulsion. While these low vaporization properties are generally advantageous in reducing the fire vulnerability of aircraft, it should be pointed out that under some circumstances this property can work against the desired objective. While it will take much longer for a fuel tank to become explosive with the fuel emulsions, it will take a corresponding greater length of time to reach the "rich limit" in the tank; thus, a tank will be explosive for a longer period of time once the "lean limit" has been passed. For example, if liquid JP-4 reaches the "lean limit" in 30 seconds, it may be expected to reach a "rich limit" in 3 to 5 minutes. The emulsions which reach the "lean limit" in about 5 minutes will take 30 minutes or more to reach a rich limit, and the WSX-7165 will take 5 to 10 hours to reach the rich limit in this test chamber. The equilibrium mixture for most Army aircraft operating conditions will be well beyond the rich limit; thus, a thorough analysis of the advantages or disadvantages of this property must consider the mission profile, altitude changes, fuel consumption rates, slosh and vibration, etc.

C. MINIMUM VENT AIRFLOW RATES TO PREVENT EXPLOSIVE VAPOR FORMATION

A stream of venting air through a fuel tank will continuously remove some fuel vapor from the tank if only fresh air is brought in and the exhaust stream contains fuel and air. If the fuel vaporization rate were truly constant, an air change per time interval to reach the explosive mixture (30 seconds for JP-4, etc.) would be required. In this test chamber, the fuel quantity was far from infinite and the fuel was not maintained in an isothermal condition; thus, fuel vaporization rates decrease as the test proceeds. This permits the elimination of the explosive hazard with somewhat less air than constant vaporization would predict. Figure 14 presents the results of this series of tests with the four fuels. Very

reproducible data were possible with the first three fuels. With the WSX-7165, it was not possible to measure vent airflow rates to the extremely low levels required to permit an explosive accumulation of fuel vapors. The value shown on Figure 14 for this fuel is an estimate, but it is sufficiently accurate for any practical purpose.

The use of a vent airstream through the vapor space of tanks containing emulsified fuel is clearly a very practical way of eliminating the vapor space explosion hazard. It is probable that vapor space protection for a 100-gallon tank of WSX-7165 emulsion could be provided at an airflow rate of about 1/4 cubic foot per minute and that similar protection could be given MEF or EF4-104 emulsions at an airflow rate of no more than 4 or 5 cubic feet per minute. These are rates which are easily achieved by impact air alone and could be provided in aircraft at a minimum weight penalty and dollar cost.

This is not a practical approach with liquid fuels for the following reasons. First, as much as 50 cubic feet per minute of venting air would be required to protect the 100-gallon tank of fuel if the surfaces could be held quiet in flight. To the extent that sloshing and misting of fuel take place in a particular tank, additional vent air would be required. The emulsified fuels are much less subject to sloshing than is the liquid. Second, the amount of fuel leaving the system in the vent air, just to prevent the explosive mixtures, becomes significant at high vent rates. This fuel loss could impose a substantial weight penalty if vent air were used to protect aircraft which burn liquid fuels. Thus, vent air protection is recommended for the tanks on any future Army aircraft employing fuel emulsions, but vent air is not recommended for present aircraft fuel systems.

D. EXPLOSIVE VAPOR FORMATION RATES THROUGH THIN BLADDER MATERIAL

Earlier studies have proposed the use of fuel bladders as a means of reducing the tank vapor space explosion hazards or as a means of achieving fuel flow from an emulsion- or gel-filled tank. The investigation completed under this phase of the project yields quantitative data relative to the

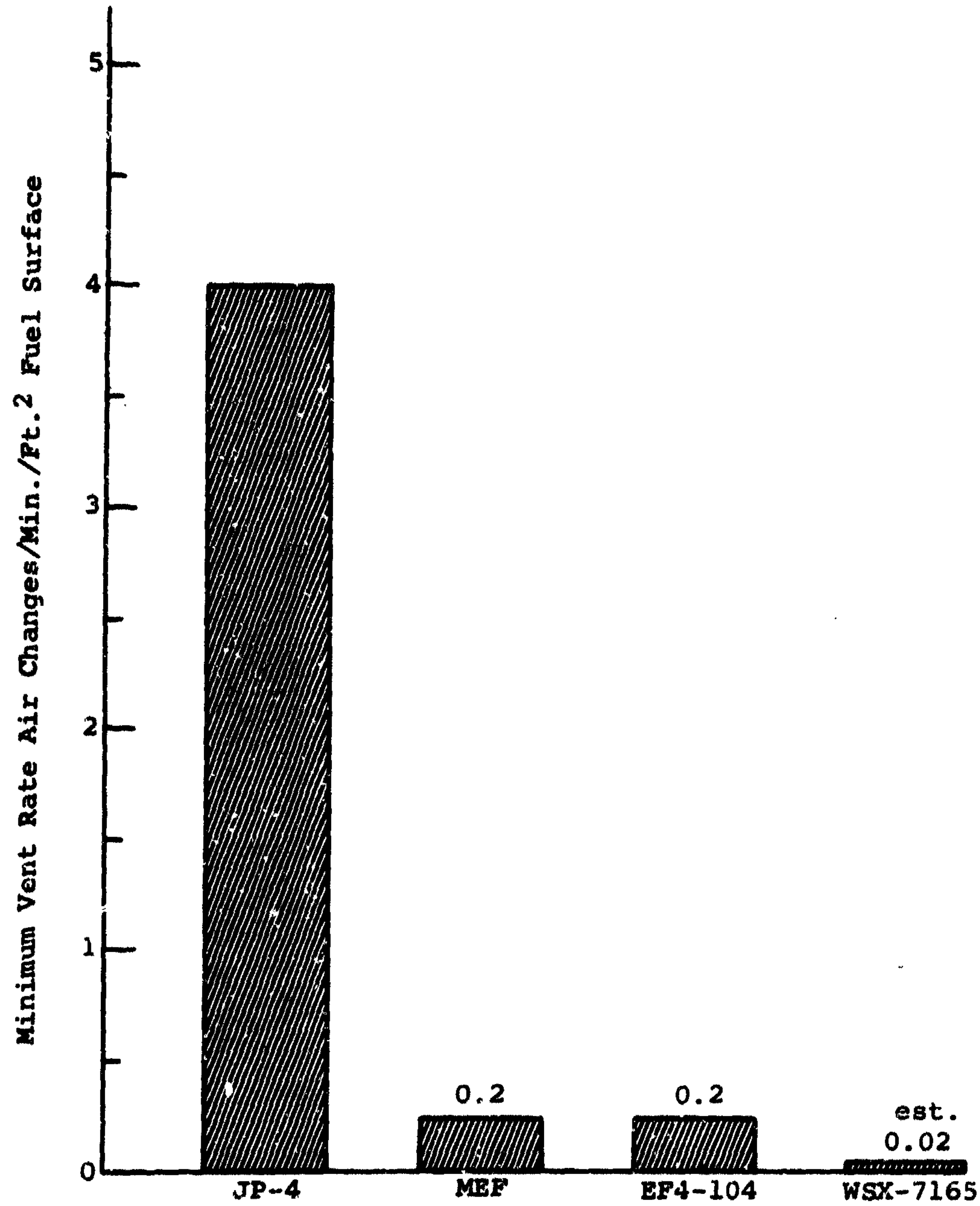


Figure 14. Minimum Tank Vapor Space Vent Rates to Prevent Explosive Fuel-Air Mixtures.

fuel permeability of one candidate material and provides a basis for estimating the fuel permeability of thicker bladders of this material or bladders formed from other materials.

The same explosive test chamber was used for the bladder investigation as for the studies reported in sections B and C. A series of tests was completed with liquid JP-4 and each of the three emulsions.

The bladder material selected was a 4-mil clear polyethylene film manufactured by the Ethyl Corporation. Bladders which would just fit in the pan used for the open fuel tests were formed from this sheet material. Fuel was then placed in each bladder, air was removed, and finally the bladder was sealed with heat. Filled bladders were carefully inspected for signs of leakage after sealing. Only those which were completely sealed were used in the explosive vapor tests. All sealed bladders were permitted to stand at least 24 hours after filling so that equilibrium permeation rates through the bladder could be achieved. The filled fuel bladders were dry to the touch and gave no visual indication of fuel loss. Periodic weighing of the bladders showed that they continued to lose weight at a nearly constant rate for many hours. The average rate of fuel loss from these filled bladders over a period of five days was as follows.

TABLE I
FIVE-DAY WEIGHT LOSS RATES FOR FUEL IN BLADDERS

Fuel Type	Permeation Rate
JP-4	0.95 gram/hour
MEF	0.55 gram/hour
EF4-104	0.65 gram/hour
WSX-7165	0.50 gram/hour

A slight tendency for the permeability rate to rise briefly following handling was noted, but in general the rates were quite constant and did not differ greatly even between fuels. This indicates that the permeation of the polyethylene film is the controlling rate process involved.

Lean explosive mixtures above the bladders were spark initiated in the test chamber at times between 1-1/2 and 2 hours for JP-4, MEF and EF4-104. As might be expected, there was a significant scatter in these data; however, no explosions were possible in less than 90 minutes with any fuel, and explosions were repeatedly achieved at times between 90 and 120 minutes with each of these fuels. The WSX-7165 fuel never produced an explosive vapor mixture in the tests completed. The reason for this is not clear, since the weight loss rate for this emulsion is quite close to those for the other emulsions tested. Explosions were expected at about 2 hours, but repeated attempts at times from 1 hour to 8 hours, failed to produce explosions, even though weight loss values clearly indicate that enough fuel vapor was present. A butane torch was used to ignite the fuel vapor through the pressure relief diaphragm following one test of the WSX-7165 fuel which had run for 5 hours. The vapors were ignited with difficulty, and only a very soft blue flame propagated through the chamber. This had the appearance of a mixture which was below the lean limit, but weight loss data indicated that nearly twice the minimum amount of fuel vapor was present. It may be assumed that some additive of the fuel emulsion inhibited flame propagation under these test conditions, but the scope of the program did not permit a thorough investigation of this phenomenon.

E. CONCLUSIONS

1. These data indicate that the fuels of interest will permeate a polyethylene bladder and very probably would permeate any other elastomeric material that can be wetted by the fuel.

2. The permeation rates are of the order of 1 to 3 grams per hour per square foot of bladder for a 4-mil-thick material. Thicker materials should produce proportionately lower escape rates for the fuel.

3. A small vent airstream through the vapor space of collapsible bladder tank containers should be sufficient to prevent explosive fuel-air mixtures from forming outside the bladder. This is true for liquid JP-4 or for any of the emulsified fuels.

4. The apparent lack of explosive mixtures above bladders filled with WSX-7165 fuel cannot be fully explained at this time. This apparent behavior may have implications to the previous explosive vapor formation rate studies.

IV. FUEL DISPERSION STUDY

The semisolid nature of the emulsified fuels is one of their most outstanding properties. This property will reduce or eliminate the drainage of fuel from a damaged fuel tank and will have some effect on the splatter and droplet breakup patterns of fuels subjected to even the most severe impact conditions. Two such conditions were selected for study with the fuel emulsions under investigation. First, the fuel breakup patterns associated with fuel falling onto a hard, flat surface, such as a runway, were determined; second, the spray patterns associated with bullet impacts on aircraft fuel tanks were investigated. These conditions relate to the hazards associated with crash fuel fires and with flight fuel fires started by incendiary ammunition. The detailed test plan for the study of fuel dispersion is given in Appendix II.

A. FUEL DROP SPLATTER AND DISPERSION

The tests involving fuel falling onto the hard, flat surface were conducted under the conditions indicated by Figure 15. Three drop heights were used in these tests: 5, 10, and 20 feet. The fuel mass was contained within a 1/2-mil polyethylene film and was approximately spherical in shape. The drops were started by a solenoid release mechanism, and the fuel was guided to the impact point by a pair of vertical wires. The tests were conducted outdoors, but great care was exercised to insure that ambient wind conditions did not influence the tests. Drops were made only when the air was still. Fuel impacts with the concrete surface were photographed at a rate of 2000 frames per second. This permitted a rather detailed determination of the way in which the fuel mass deformed, expanded, and eventually broke up into individual droplets which were scattered through the air following an impact. Figures 16 and 17 show three frames from the films of typical fuel drops. In each instance, the fuel is observed to first spread and then rebound upward in an expanding, roughly hemispherical mass. This body of fuel is a continuous mass or a closely packed group of droplets which appears nearly continuous for some distance. Finally, the fuel breaks up

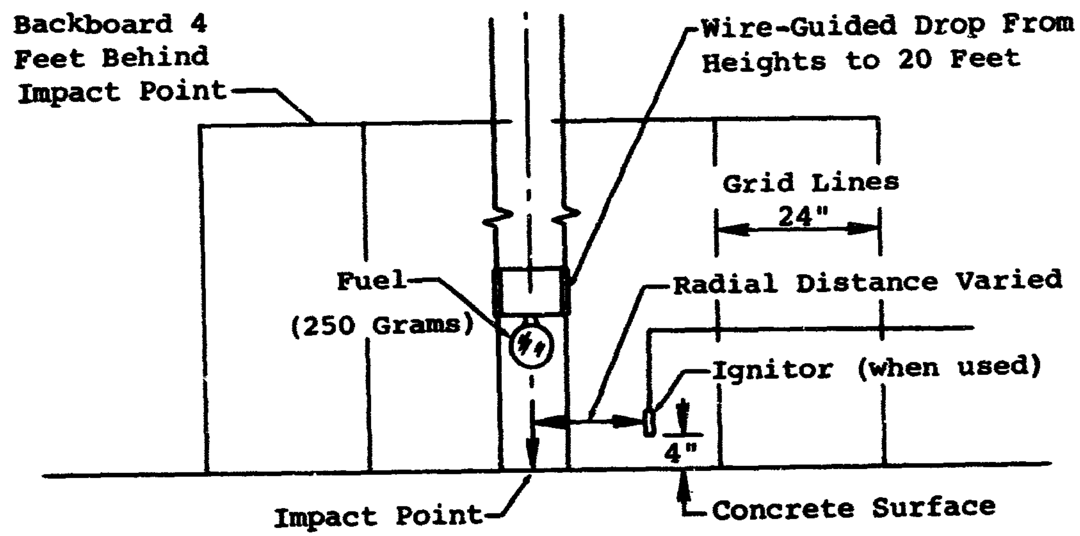


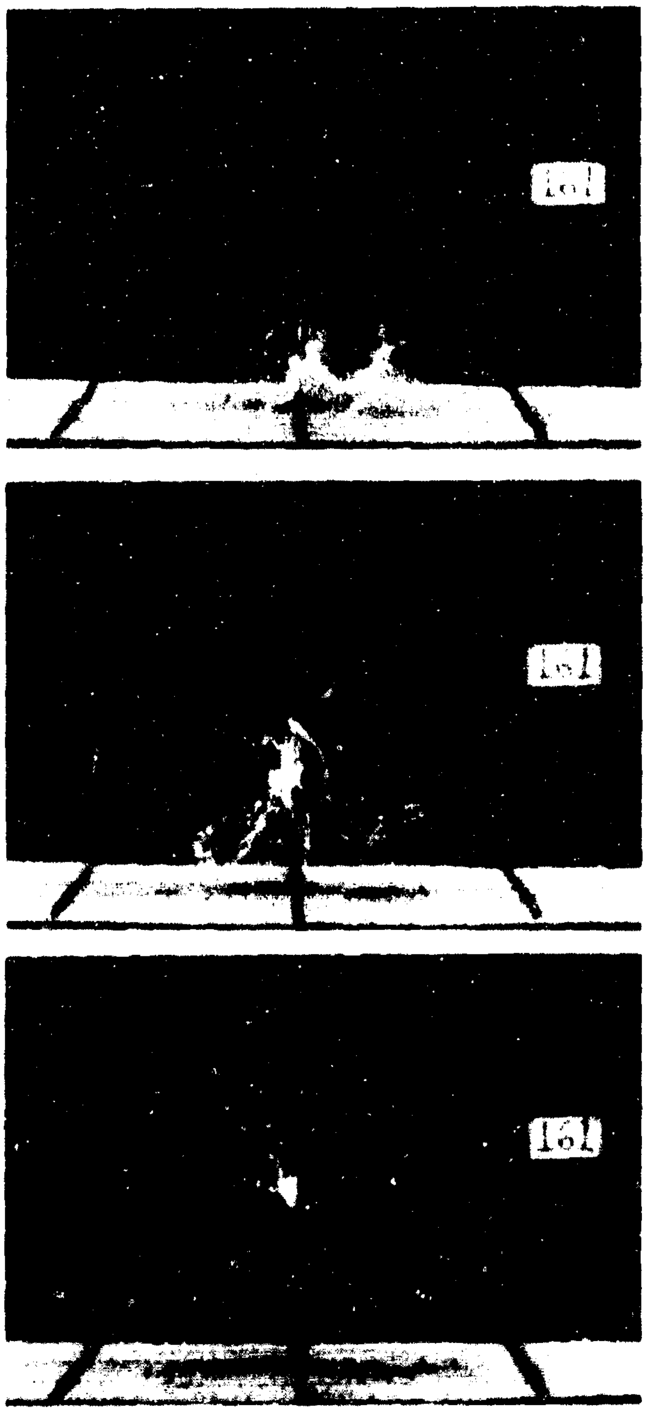
Figure 15. Arrangement of Test Components for Fuel Drop Dispersion and Ignition Evaluation.

23 Milliseconds
After Impact

65 Milliseconds

111 Milliseconds

Figure 16. The Development of JP-4 Spray for a 20-Foot Drop Onto a Concrete Surface.



32 Milliseconds After Impact

132 Milliseconds

251 Milliseconds

Figure 17. The Development of an MEF Emulsified Fuel Spray for a 20-Foot Drop Onto a Concrete Surface.

into separate droplets or chunks, which fly through the air until the force of gravity brings them to the surface again. Individual fuel particles spread as far as 10 or 15 feet from the drop point on each test. A careful analysis of the film records showed that the closely packed fuel expanded to a radius of 1-1/2 to 2-1/2 feet before discrete particles of fuel could be clearly observed. The drops from 20 and 10 feet were not significantly different in this respect. Drops from a height of 5 feet did not produce consistent rupture of the thin film containing the fuel, and thus the 5-foot drops were not subject to detailed analysis.

A slight difference in the radius of expansion before individual fuel droplets became visible was apparent for two of the fuel emulsions. Liquid JP-4 and the EF4-104 emulsion expanded to radii of 1.2 to 1.7 feet, while the MEF and WSX-7165 emulsions appeared to cohere longer to radii of 2.0 to 2.8 feet. The particles of fuel which continued beyond these radii were substantially larger for all of the emulsified fuels than for the liquid JP-4. The photographic resolution was not great enough to permit accurate determination of the size or number of particles produced, but an examination of Figures 16 and 17 will indicate the larger particles present with the emulsified fuel.

Figures 18 through 27 show the types of fuel patterns that were made on the concrete surface and the backboard by these fuel drops. It should be noted that much of this fuel on the surface results from the second hit of the fuel rather than the first. It is clear that a major proportion of the fuel rebounds from the surface after the first impact. However, much of this fuel is projected upward within 1 or 2 feet of the original axis of the drop, and thus most of it again falls to the surface near the original impact point. Liquid JP-4 produces an area of several square feet that is continuously wetted. The emulsified fuels produce smaller continuously wetted areas and show a substantial number of blotches of fuel which are remote from the impact point.

Fire will propagate over the continuously wetted areas with any of these fuels, but generally fire will not propagate between separated spots of fuel on the surface. The reduction in the size of the continuously wetted surface areas for the emulsified fuels is a significant advantage for

Figure 18. Liquid JP-4 Spillage and Splatter Pattern for 250 Grams Dropped From 20 Feet.

Figure 19. Liquid JP-4 Fuel Splatter Pattern on Concrete Surface for 250 Grams Dropped From 20 Feet.

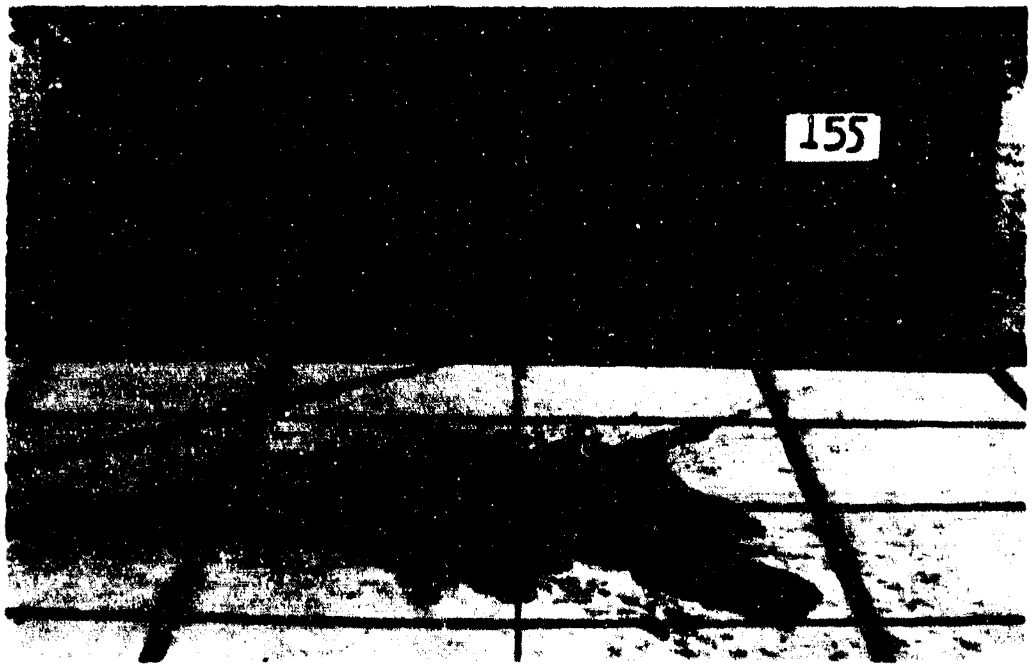


Figure 20. Liquid JP-4 Spillage and Splatter Pattern for 250 Grams Dropped From 10 Feet.

Figure 21. Liquid JP-4 Fuel Splatter Pattern on Concrete Surface for 250 Grams Dropped From 10 Feet.

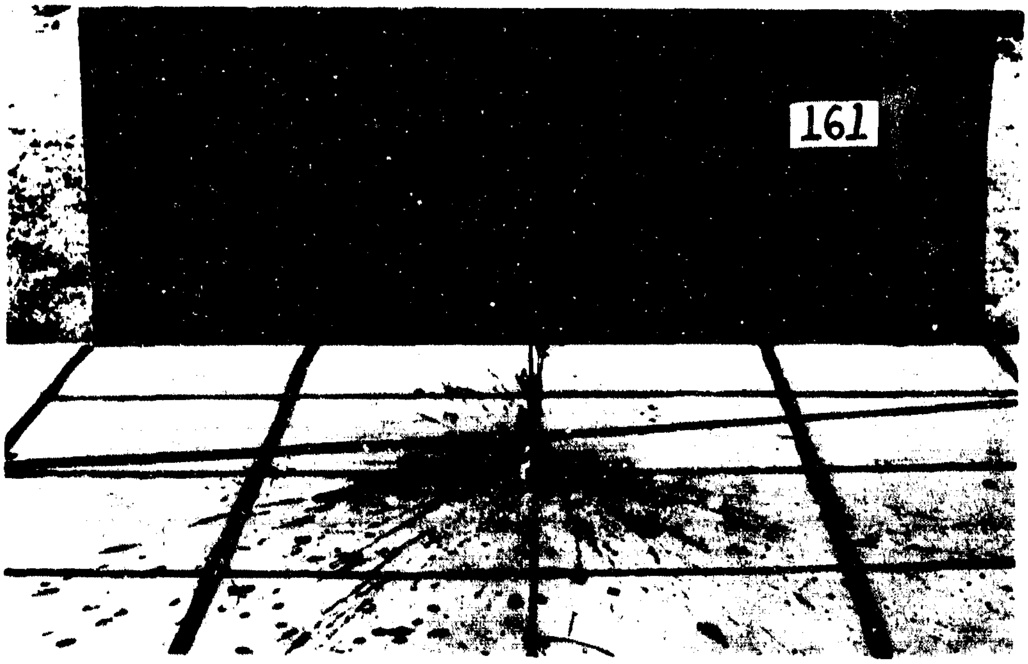


Figure 22. MEF Fuel Emulsion Splatter Pattern for 250 Grams Dropped From 20 Feet.

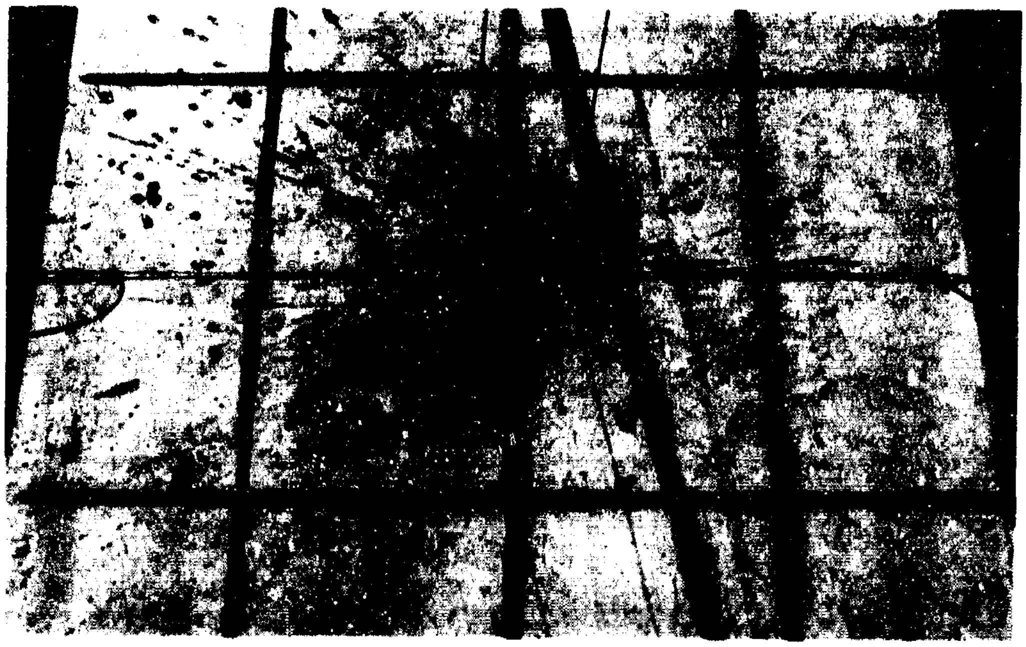


Figure 23. MEF Fuel Emulsion Splatter Pattern on Concrete Surface for 250 Grams Dropped From 20 Feet.

Figure 24. EF4-104 Fuel Emulsion Splatter Pattern for 250 Grams Dropped From 20 Feet.

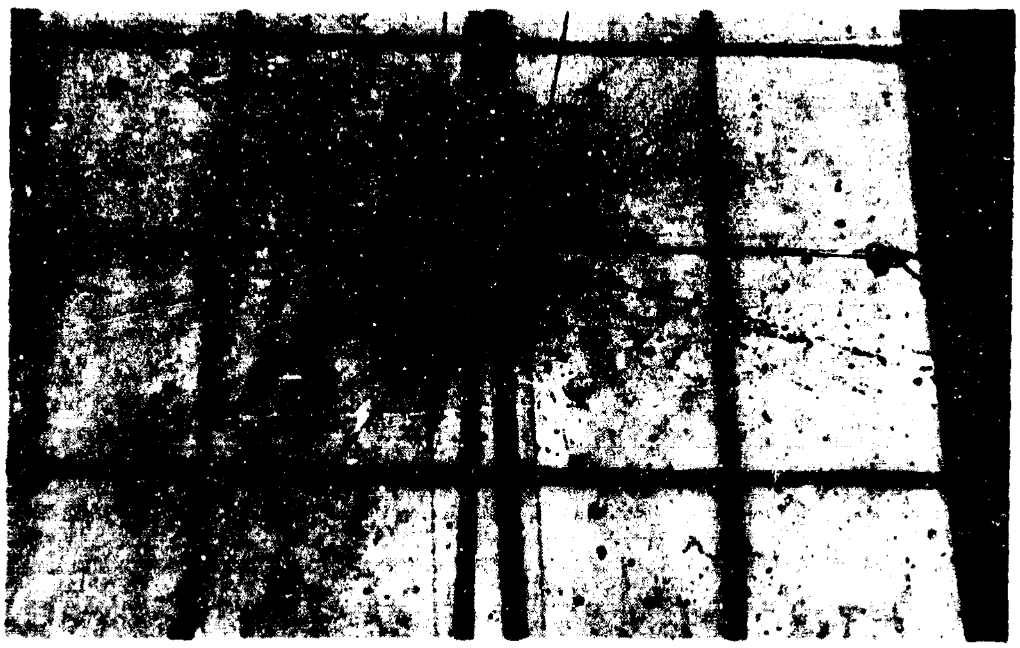


Figure 25. EF4-104 Fuel Emulsion Splatter Pattern on Concrete Surface for 250 Grams Dropped From 20 Feet.

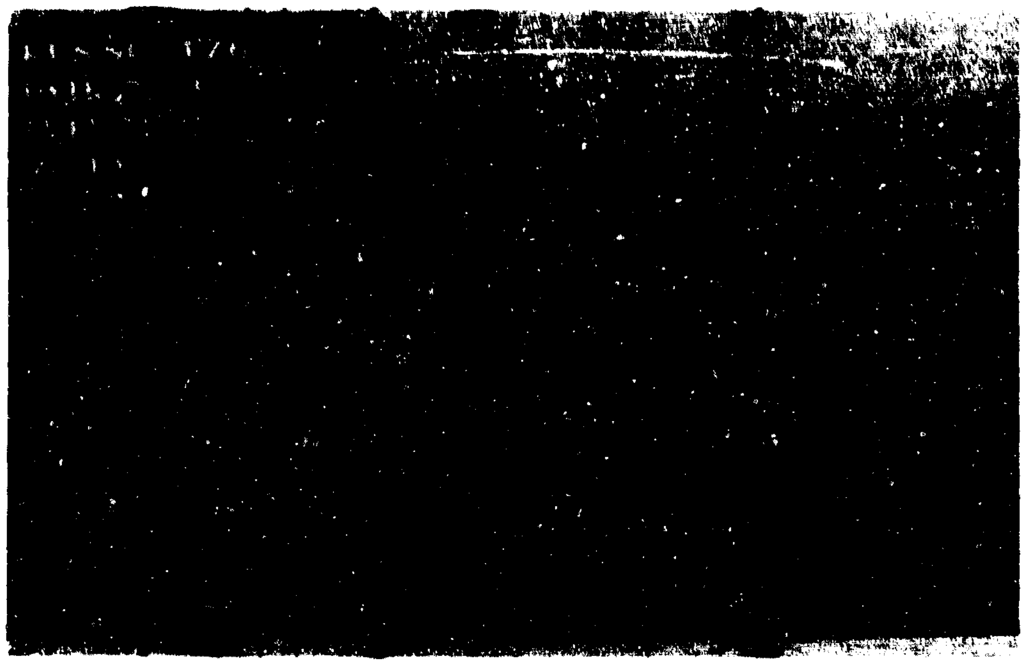


Figure 26. WSX-7165 Fuel Emulsion Splatter Pattern on Backboard for 250 Grams Dropped From 20 Feet.

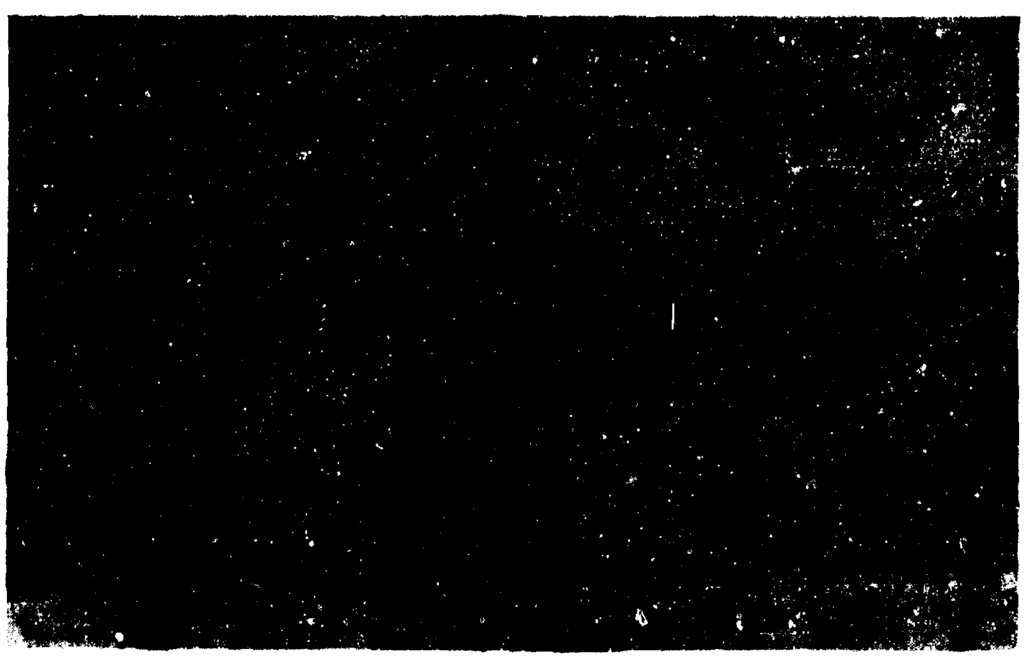


Figure 27. WSX-7165 Fuel Emulsion Splatter Pattern on Concrete Surface for 250 Grams Dropped From 20 Feet.

these fuels. The increased size of the individual particles of fuel with emulsions is also considered to be an advantage, since it reduces the probability of a droplet's encountering an ignition source, reduces the fuel surface in the cloud from which vaporization can take place, and may tend to make ignitions more difficult because of the cooling effect of a large drop of fuel's encountering a small heat source.

B. BALLISTIC RESEARCH LABORATORIES FUEL NOZZLE DISPERSION

It has long been known that an incendiary bullet ignites a spurt or spray of fuel which is forced out of the tank after the bullet enters. This spray leaves through the hole made by the bullet as it entered and is caused by the high pressure which results from the kinetic energy exchange between the bullet and the fuel. The nature of this fuel spray is partially dependent upon the bullet velocity, tank material, and tank geometry; but over a substantial range of the most frequently occurring values of these parameters, the sprays are quite similar and occur in 5 to 7 milliseconds after bullet impact. Often it is possible to observe a second or perhaps even a third distinct spray at substantial time intervals after the first spurt. These are the result of the pressure wave's bouncing back and forth between the tank walls as the energy left by the bullet is expended.

Lethality testing with aircraft fuel tanks is quite expensive and does not always permit the precise control of test parameters which is desired. The staff of the Ballistic Research Laboratories (BRL) at Aberdeen Proving Ground, Maryland, found that a caliber .50 cartridge case filled with fuel could be electrically primed and fired in an aircraft target environment with excellent results. The spray from this equipment, which was referred to as the BRL fuel nozzle, or the BRL fuel spray device, closely resembled the spray from caliber .50 bullet hits on self-sealing fuel tanks. The quantity, velocity, and dispersion patterns of fuel nozzle tests were acceptably close to the similar values determined for actual fuel tanks; thus, the fuel nozzle was used extensively as a research tool at BRL, at Frankford Arsenal, and at the University of Denver in their study of incendiary ammunition performance.

Fuel nozzle tests were included in this study of emulsified fuels because they were a convenient means of evaluating differences in the spray characteristics of the semisolid fuels at a minimum cost.

These tests were performed with specially prepared caliber .50 cartridge cases to insure that the test results were as uniform as possible. Cases were cleaned and primed with electric primers and checked to be certain that their mouths were round and smooth. These nozzles were carefully filled with fuel just prior to each test. Care was taken to insure that air was not included with the fuel in the nozzle, and the mouth of the cartridge case was covered with a piece of light tissue paper to retain the fuel when it was in the horizontal firing position.

The nozzles were fired horizontally as shown by Figure 28. The fuel spray was photographed at 5000 frames per second and appeared as a shadow because of the strong backlight provided by the fresnel lens. Figure 29 presents the spray pattern of liquid JP-4 as it emerges from the nozzle at about 200 fps. Similar tests were repeatedly photographed with each of the fuels under investigation. Measurements of the spray envelope were then made from the film records.

To obtain the measurements of the spray envelope for the various fuels, these high-speed motion picture sequences were projected and tracings of selected frames were made. From the geometry of the experimental setup, an accurate distance scale was determined for the midplane of the spray. Using this scale information with the tracings of the spray envelopes, approximate diameters of the spray plume were determined for three distances out from the nozzle. One-half the measured diameters are the values reported in Table II for the radius values. The spray plume is randomly asymmetric to the axis of the nozzle, so the tabulated values are to be considered only as approximations. The velocity values were determined from the space dimension information and the measured framing rate of the high-speed camera for each shot. These data are averages from at least four tests with each fuel and are presented in Figure 30.

These data indicate that the emulsified fuels have only a slight tendency to cohere when projected through the air at

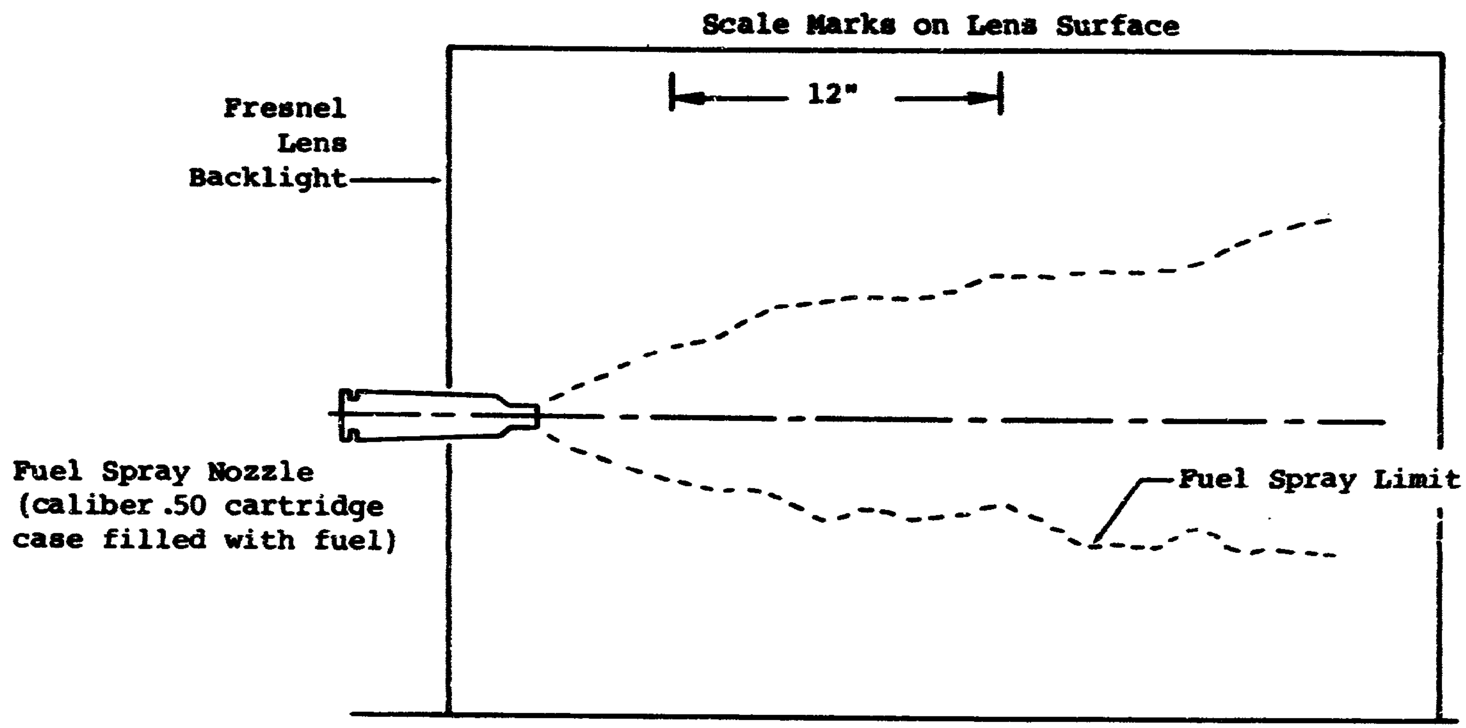
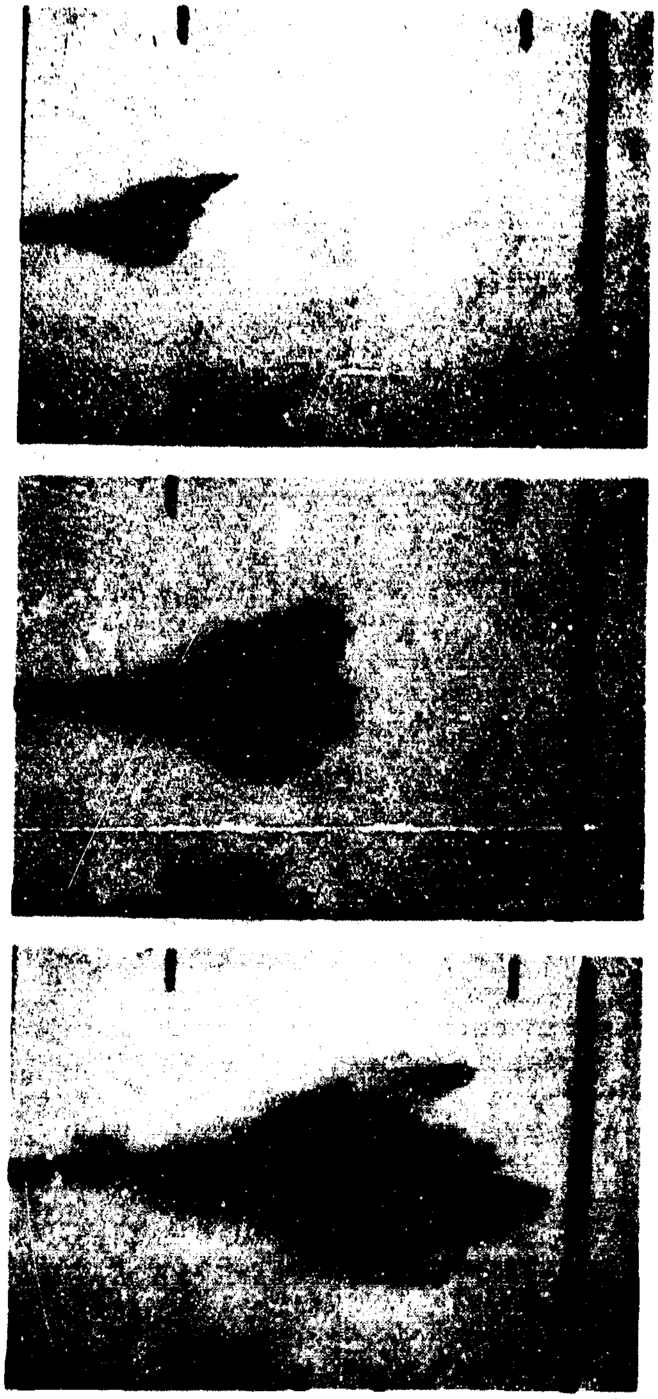


Figure 28. Arrangement of Test Components for BRL Fuel Spray Dispersion Evaluation.



1 Millisecond After Firing

3 Milliseconds

7 Milliseconds

Figure 29. Liquid JP-4 Spray Emerging From the BRL Fuel Nozzle.

TABLE II

RADII OF BRL FUEL SPRAYS FOR JP-4 AND EMULSIFIED FUELS

Fuel Type	Average Spray Radius (in.) at Increasing Distances From Nozzle: 6 inches	12 inches	18 inches	Average Spray Velocity (ft/sec)
Liquid JP-4	2.1	3.0	3.2	250
MEF	1.8	2.7	2.7	200
EF4-104	2.1	3.0	3.2	200
WSX-7165	1.2	1.7	2.2	140

these high velocities. The dispersion patterns are slightly narrower for the semisolid fuels, but generally they were sprayed from the nozzle in dispersions of fine droplets which were not greatly different from sprayed liquid JP-4. It is probable that the shear forces acting on the fuel in the spray are several orders of magnitude greater than the shear strength of these emulsions.

C. BALLISTIC IMPACT FUEL DISPERSION

While the BRL fuel nozzle is an economical and useful research tool, it is not quite the same as a bullet entering a tank of fuel; thus, an extensive series of tests was included in this program to determine the response of tanks of fuel to bullet impacts. Three sizes of ammunition, three types of tank material, and four types of fuel were employed in the tests; nearly every combination of these variables was checked. The ammunition types used were caliber.30 M-2 ball, caliber .50 M-2 ball, and 20 mm ball M-55A2; each was fired at its normal service velocity from a range of 100 feet. Each bullet struck the tank face at zero degrees obliquity unless otherwise noted. Thus, these hits produce the minimum amount of tank damage and the minimum amount of fuel leakage for a given set of test conditions. The test fuel tank was set up as shown in Figure 31. The tank panels were clamped between flanges for all tests. For caliber .30 and caliber .50 tests, a steel cylindrical tank was used, with test panels on the ends of the

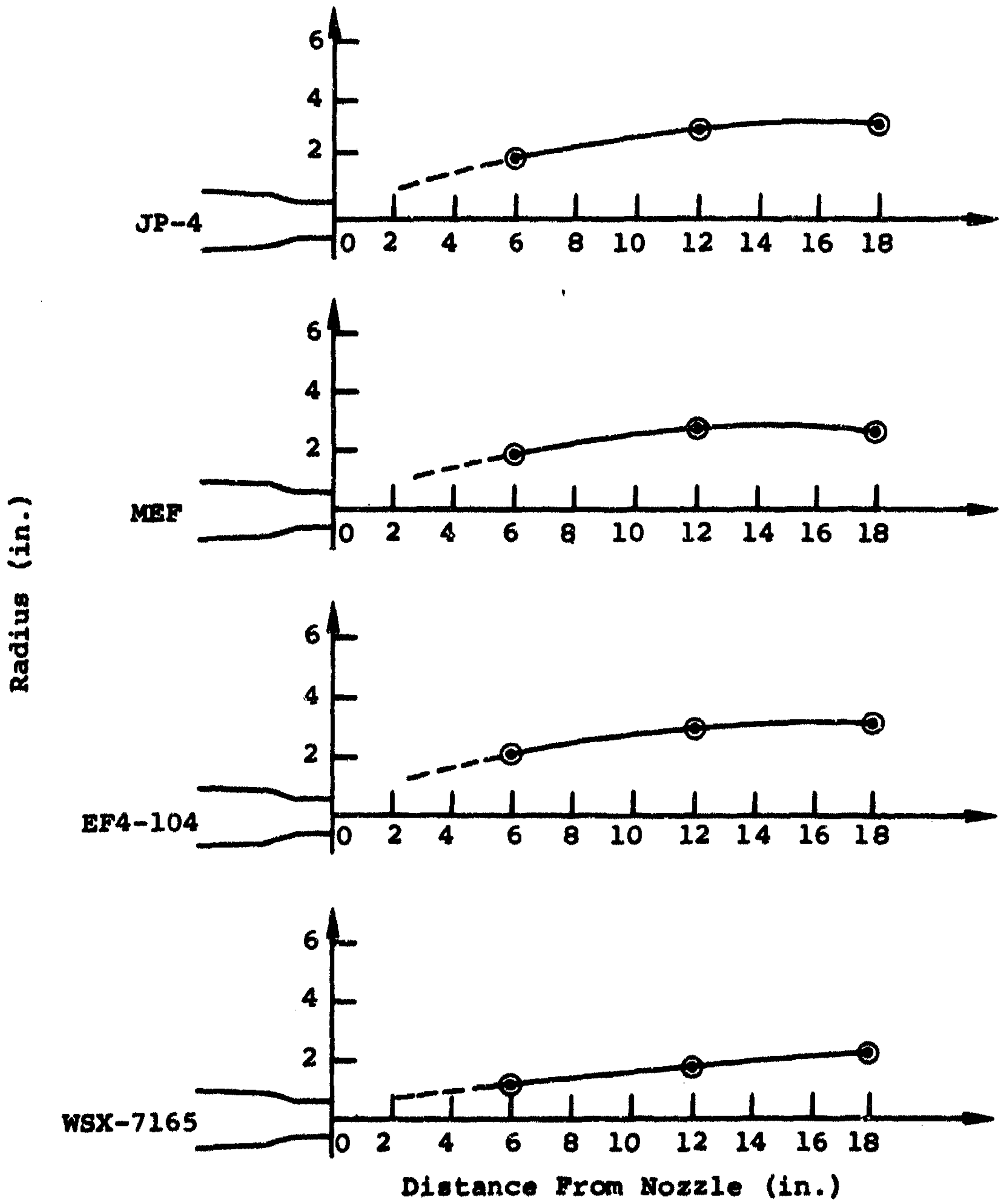


Figure 30. Fuel Spray Dispersion Patterns From the BRL Fuel Nozzle.

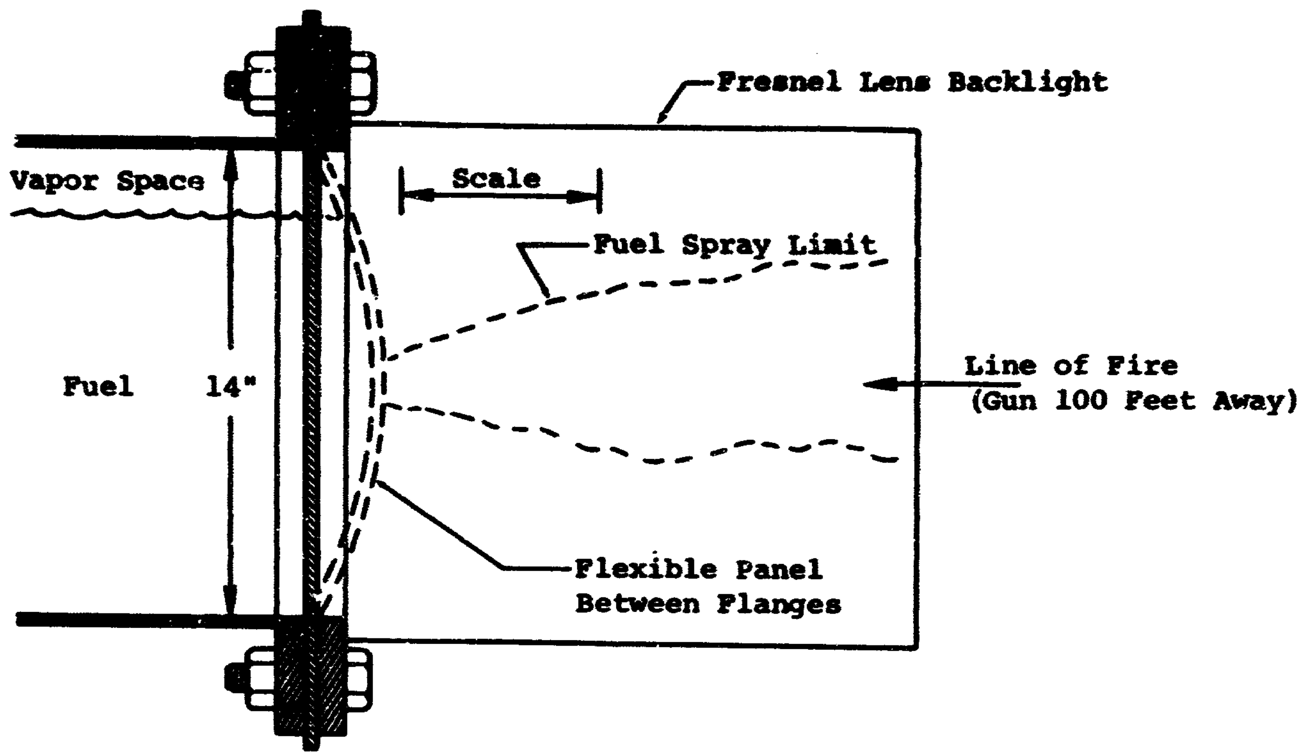


Figure 31. Arrangement of Test Components for Ballistic Impact Fuel Spray Evaluation.

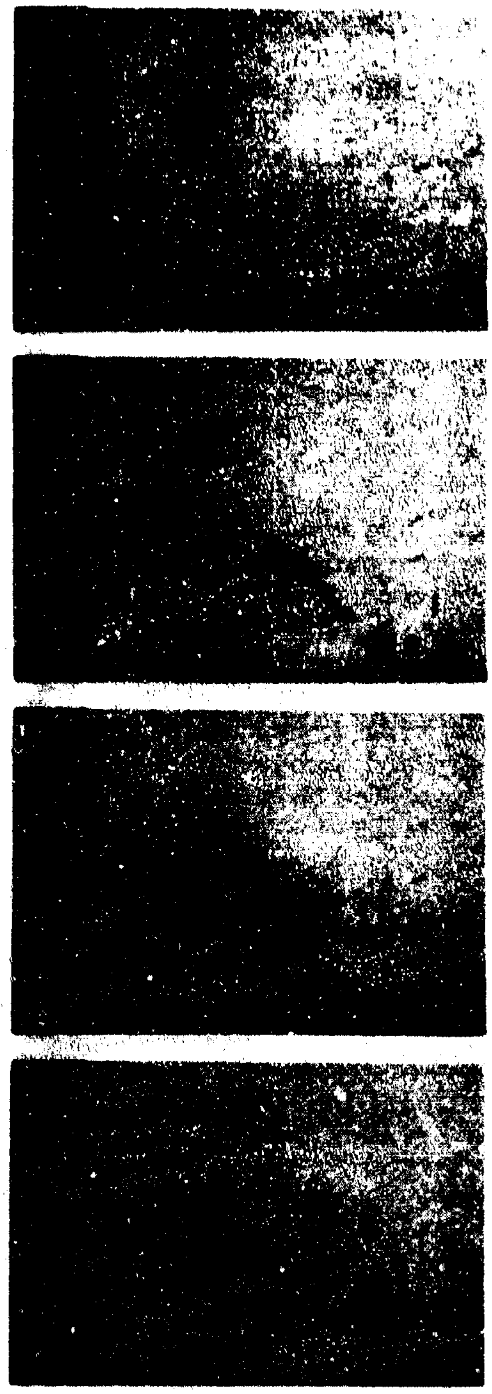
cylinder for bullet entrance and exit. This tank had a 14-inch inside diameter and was 36 inches long. For the 20 mm tests, 2-foot self-sealing cube tanks were used. The test panel material was clamped between flanges on the entrance side of the cube, and a circle, 14 inches in diameter, of the original tank material was removed so that the new panel was in fact the wall of the test tank. The cubical tanks were held in place by angle iron supports on the four vertical edges of the tank, and 1/4-inch plywood was used as a backing board on the bottom, sides, and exit faces of the cube. The top of the tank was closed with a steel plate but the tank was filled only to about 80 percent of its capacity.

All of the ballistic fuel dispersion tests were witnessed by a high-speed 16 mm framing camera running at a rate of about 5000 frames per second. The same backlighting technique was employed in these ballistic dispersion tests as had been previously used in the fuel spray tests.

Figure 32 presents several frames from a typical film record. In this instance, a caliber .50 M-2 ball projectile has perforated a crash-resistant tank panel which was containing the EF4-104 fuel emulsion. A frame-by-frame analysis of these records provides a determination of the time interval from bullet entry to the start of the fuel spray, the rate of spray emergence, and the pattern or size and shape of the spray produced.

Some variation in each of these variables was found; however the time from bullet entry until the spray emerged was generally between 5 and 7 milliseconds. Shorter time delays were generally associated with hits that were closer to the edge of the panel or to panel materials that were more rigid. Longer times were noted for well-centered hits or panels that were more flexible, such as the crash-resistant panels.

The velocity of spray emergence varied somewhat with the location of the tank wound relative to the edge of the panel and with the shape of the tear or wound made, but most spray velocities fell between 50 and 100 fps. Thus, actual spray velocities are somewhat lower than the BRL fuel nozzle velocities, but the difference is not great enough to degrade seriously the validity of BRL fuel nozzle data.



7 Milliseconds
After Impact

10 Milliseconds

16 Milliseconds

19 Milliseconds

Figure 32. Caliber .50 Ballistic Fuel Spray Emerging From a Tank of EF4-104 Fuel Emulsion Confined by a Crash-Resistant Tank Panel.

The dispersion patterns were determined by tracing the spray at various time intervals during its emergence from the tank wound in a manner similar to that for the BRL fuel nozzle analysis. The radius of the spray was measured as it swept past distances of 6, 12, and 18 inches along the spray axis and generally normal to the tank wall. Thus, a fuel spray envelope was defined for each spray, out to a distance of 18 inches from the tank. Within this region, a spray of fuel droplets must be expected for the test conditions reported. Outside these limits, the fuel spray is unlikely. It should be noted that the spray patterns reported are for the visible spray, and it is possible that some fuel vapor exists outside these limits. This is particularly probable at greater distances from the tank wall. Here, the fuel breaks up into droplets which are too small to be seen by the camera, or perhaps the fuel is completely vaporized and therefore not visible.

The results of the ballistic dispersion analysis are presented in Tables III through X and are graphically shown in Figures 33 through 40.

TABLE III
THE DIMENSIONS OF FUEL SPRAY DISPERSION PATTERNS FOR CALIBER .30 BALLISTIC IMPACTS ON CONVENTIONAL SELF-SEALING PANELS

	Spray Radius (in.) at Increasing Distances From the Tank Wall		
Fuel Type	6 inches	12 inches	18 inches
Liquid JP-4	0.7	1.1	0.0
	0.4	0.0	0.0
	0.0	0.0	0.0
	Av. 0.4	Av. 0.4	Av. 0.0
MEF	0.2	0.0	0.0
	0.0	0.0	0.0
	Av. 0.1	Av. 0.0	Av. 0.0
EF4-104	1.3	1.2	0.9
	0.0	0.0	0.0
	Av. 0.6	Av. 0.6	Av. 0.5
WSX-7165	0.3	0.0	0.0
	0.5	0.7	0.0
	Av. 0.4	Av. 0.4	Av. 0.0

TABLE IV

THE DIMENSIONS OF FUEL SPRAY DISPERSION PATTERNS FOR CALIBER .30 BALLISTIC IMPACTS ON CRASH-RESISTANT PANELS

Fuel Type	Spray Radius (in.) at Increasing Distances From the Tank Wall		
	6 inches	12 inches	18 inches
Liquid JP-4	0.4	0.0	0.0
	2.2	4.0	2.4
	Av. 1.3	Av. 2.0	Av. 1.2
MEF	0.7	1.1	0.0
	0.8	1.1	1.5
	Av. 0.8	Av. 1.1	Av. 0.8
EF4-104	0.3	0.0	0.0
	0.2	0.2	0.0
	Av. 0.2	Av. 0.1	Av. 0.0
WSX-7165	1.1	1.3	0.0
	0.9	1.0	0.0
	Av. 1.0	Av. 1.2	Av. 0.0

TABLE V

THE DIMENSIONS OF FUEL SPRAY DISPERSIONS FOR CALIBER .30 BALLISTIC IMPACTS ON COAGULANT TYPE SELF-SEALING PANELS

Fuel Type	Spray Radius (in.) at Increasing Distances From the Tank Wall		
	6 inches	12 inches	18 inches
Liquid JP-4	0.7	0.0	0.0
	0.3	0.2	0.3
	Av. 0.5	Av. 0.1	Av. 0.2
MEF	0.0	0.0	0.0
	0.0	0.0	0.0
	Av. 0.0	Av. 0.0	Av. 0.0
EF4-104	0.0	0.0	0.0
	0.0	0.0	0.0
	Av. 0.0	Av. 0.0	Av. 0.0
WSX-7165	0.3	0.7	0.0
	0.0	0.0	0.0
	Av. 0.2	Av. 0.4	Av. 0.0

TABLE VI
THE DIMENSIONS OF FUEL SPRAY DISPERSIONS FOR CALIBER .50 BALLISTIC IMPACTS ON CONVENTIONAL SELF-SEALING PANELS

Fuel Type	Spray Radius (in.) at Increasing Distances From the Tank Wall		
	6 inches	12 inches	18 inches
Liquid JP-4	2.0	2.8	2.0
	1.7	2.3	2.2
	Av. 1.8	Av. 2.6	Av. 2.1
MEF	1.7	1.8	2.1
	1.0	2.0	2.0
	Av. 1.4	Av. 1.9	Av. 2.0
EF4-104	2.6	3.6	3.2
	1.8	2.5	2.6
	Av. 2.2	Av. 3.0	Av. 2.9
WSX-7165	1.1	1.5	1.5
	1.9	2.4	3.4
	1.7	1.8	1.9
	Av. 1.6	Av. 1.9	Av. 2.3

TABLE VII
THE DIMENSIONS OF FUEL SPRAY DISPERSIONS FOR CALIBER .50 BALLISTIC IMPACTS ON CRASH-RESISTANT PANELS

Fuel Type	Spray Radius (in.) at Increasing Distances From the Tank Wall		
	6 inches	12 inches	18 inches
Liquid JP-4	2.6	4.5	4.1
	3.2	3.3	3.2
	2.3	3.3	4.2
	Av. 2.7	Av. 3.7	Av. 3.8
MEF	1.9	2.5	2.4
	2.1	4.2	4.5
	Av. 2.0	Av. 3.4	Av. 3.5
EF4-104	2.2	3.4	3.8
	5.0	5.9	5.5
	Av. 3.6	Av. 4.6	Av. 4.6
WSX-7165	2.4	4.0	4.6
	1.5	2.1	2.1
	Av. 2.0	Av. 3.1	Av. 3.4

TABLE VIII
THE DIMENSIONS OF FUEL SPRAY DISPERSIONS FOR CALIBER .50 BALLISTIC IMPACTS ON COAGULANT TYPE SELF-SEALING PANELS

Fuel Type	Spray Radius (in.) at Increasing Distances From the Tank Wall		
	6 inches	12 inches	18 inches
Liquid JP-4	2.2	3.4	2.3
	2.4	3.6	4.1
	Av. 2.3	Av. 3.5	Av. 3.2
MEF	2.2	3.3	3.9
	0.6	1.1	1.4
	Av. 1.4	Av. 2.2	Av. 2.7
EF4-104	0.4	1.1	1.1
	2.0	3.9	3.1
	Av. 1.2	Av. 2.5	Av. 2.1
WSX-7165	1.2	1.7	1.7
	1.3	1.4	1.5
	Av. 1.2	Av. 1.6	Av. 1.6

TABLE IX
THE DIMENSIONS OF FUEL SPRAY DISPERSIONS FOR 20 mm BALLISTIC IMPACTS ON CONVENTIONAL SELF-SEALING PANELS

Fuel Type	Spray Radius (in.) at Increasing Distances From the Tank Wall		
	6 inches	12 inches	18 inches
Liquid JP-4	3.2	4.6	6.0
MEF*	2.2	3.0	3.0
EF4-104	2.3	1.8	-
	2.6	3.0	3.2
	Av. 2.5	Av. 2.4	Av. 3.2
WSX-7165	2.8	4.8	5.0

*These values are estimates, since this film record could not be measured satisfactorily.

TABLE X
THE DIMENSIONS OF FUEL SPRAY DISPERSIONS FOR 20 mm
BALLISTIC IMPACTS ON COAGULANT TYPE SELF-SEALING PANELS

Fuel Type	Spray Radius (in.) at Increasing Distances From the Tank Wall		
	6 inches	12 inches	18 inches
Liquid JP-4	3.4	5.1	4.4
MEF	3.5	4.4	5.0
EF4-104	2.4	4.5	4.9
WSX-7165	2.7	2.2	1.8

In addition to these simple ballistic impact tests, a few tests were performed in which the entering projectile was tumbled. Both tank entrance and tank exit fuel dispersion patterns were observed with the 5000-frame-per-second 16 mm movie camera. Bullet tumbling was achieved by 0.17 inch aluminum sheet set at an angle of 38 degrees to the line of fire and 6 feet in front of the tank. As would be expected, the panel damage was much greater for these tumbled impacts than for the straight-in impacts. The amount of fuel sprayed from the tank was also much greater, and the dispersion patterns were quite wide. These tests were performed with the 2-foot cube tanks and the panels clamped between flanges as described for the 20 mm tests.

Table XI presents the fuel dispersion data for the tumbled caliber .50 entrance tests with the four fuels, and Table XII presents similar data for tumbled exits. These data are plotted in Figures 41 and 42. Note that the radius scale values are twice the scale used previously. The panel damage on these tests varied from a tear of about 1 inch in length to rips of more than 2 inches in length. Several distinct spurts of fuel were frequently visible in the film records. It is clear that the amount of fuel sprayed from a tank by tumbled rounds passing through it is much greater than for straight-in hits.

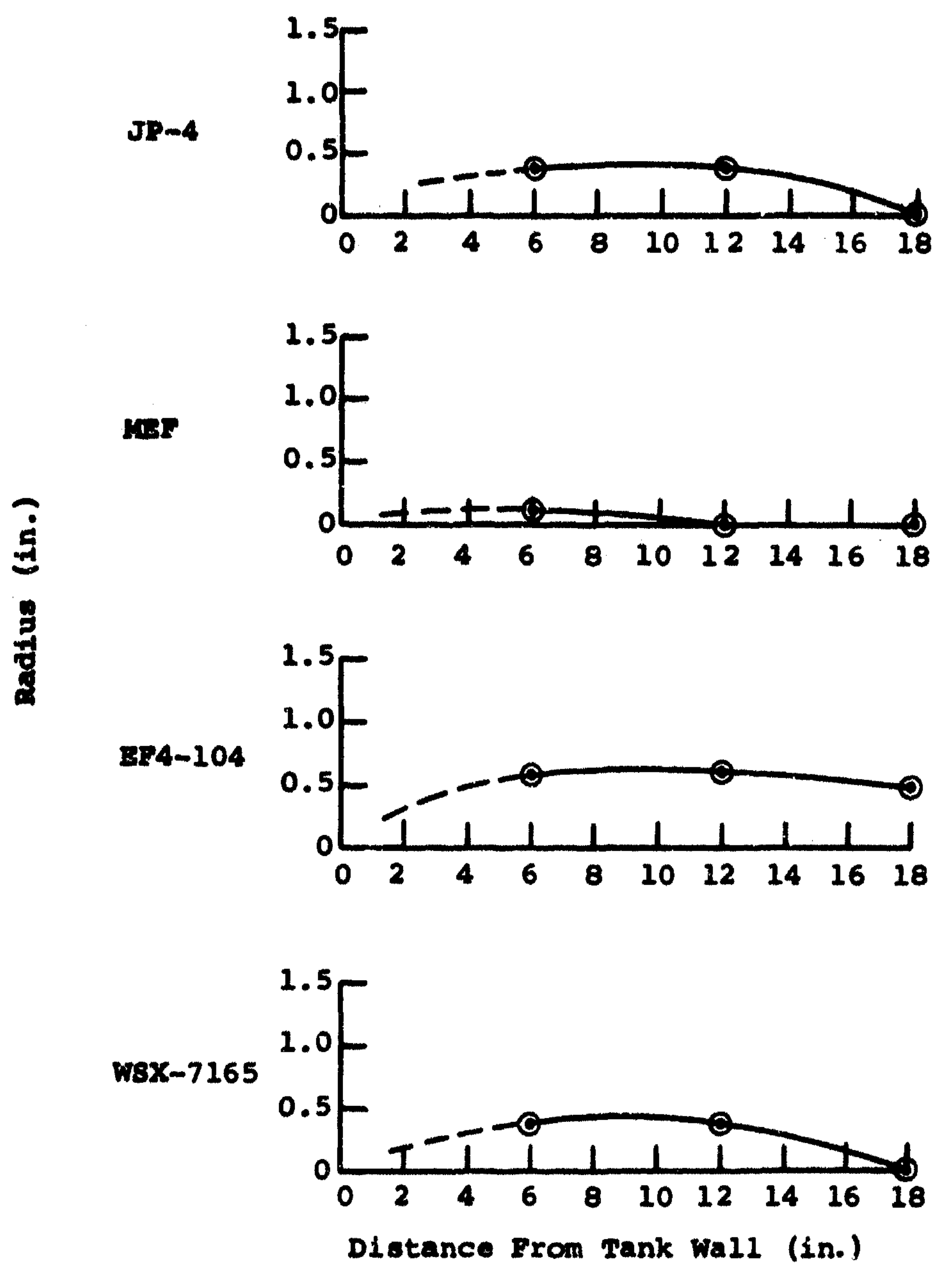


Figure 33. Fuel Spray Dispersion Patterns From Caliber .30 Ballistic Impacts on Conventional Self-Sealing Tank Panels.

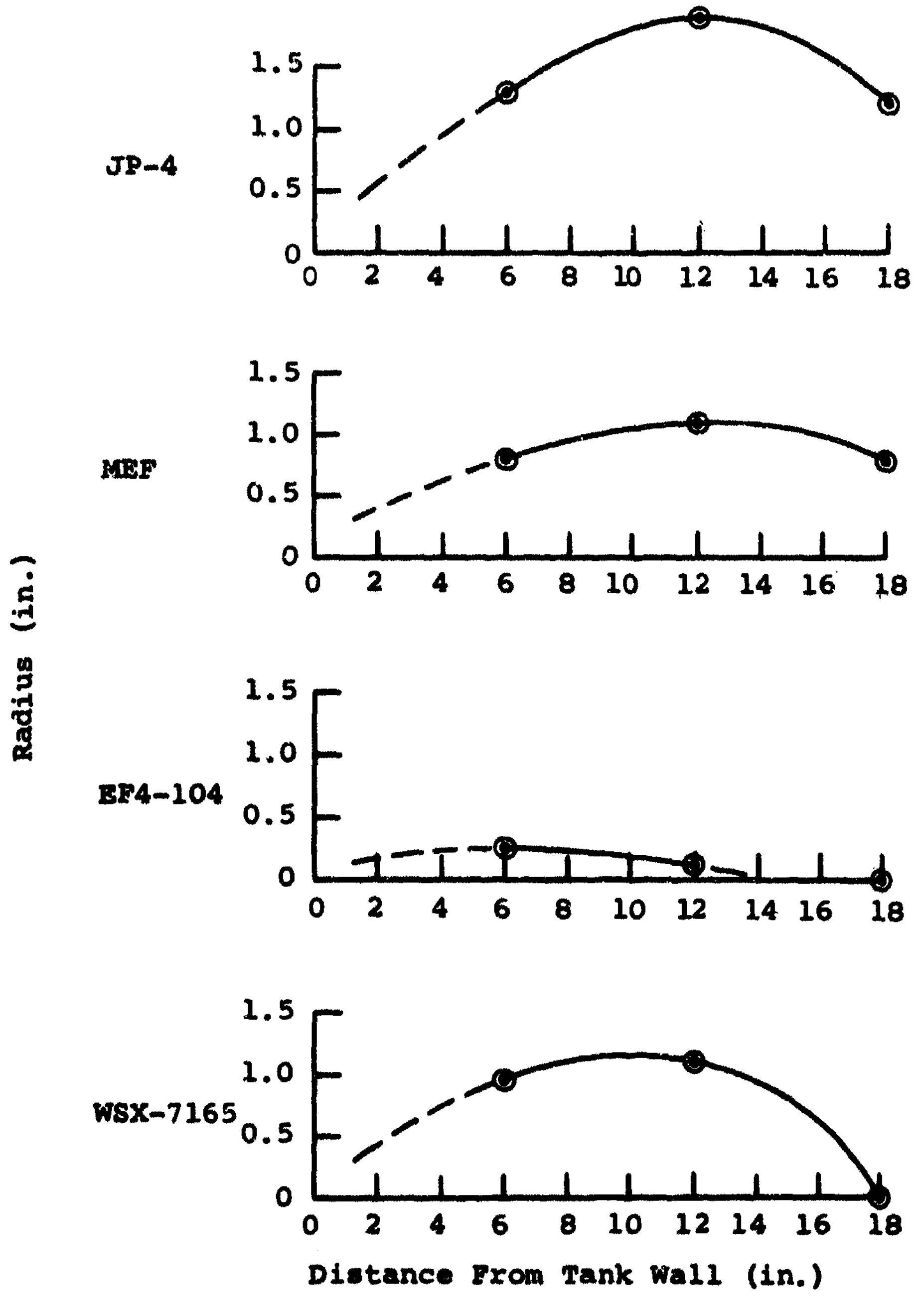


Figure 34. Fuel Spray Dispersion Patterns From Caliber.30 Ballistic Impacts on Crash Resistant Tank Panels.

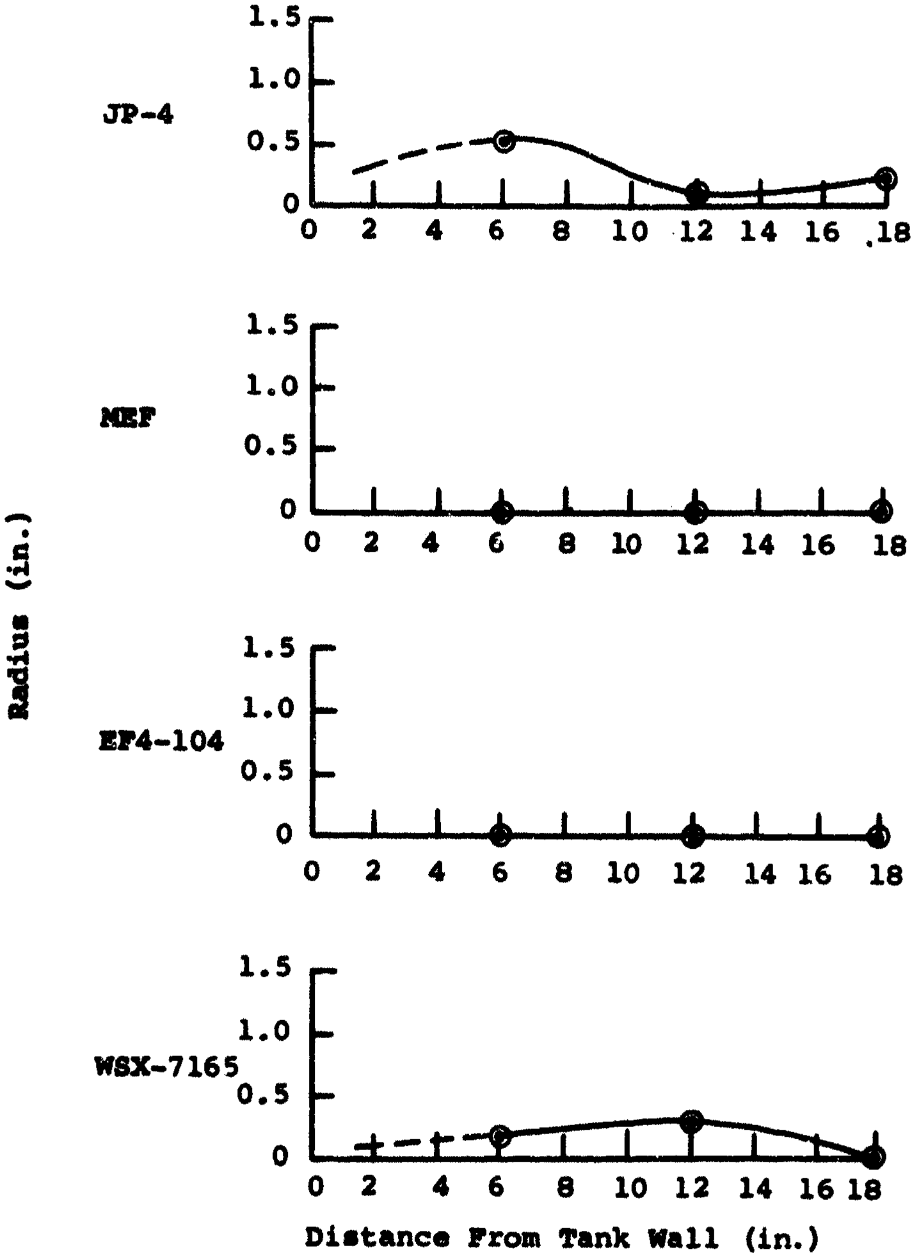


Figure 35. Fuel Spray Dispersion Patterns From Caliber.30 Ballistic Impacts on Coagulant Type Self-Sealing Tank Panels.

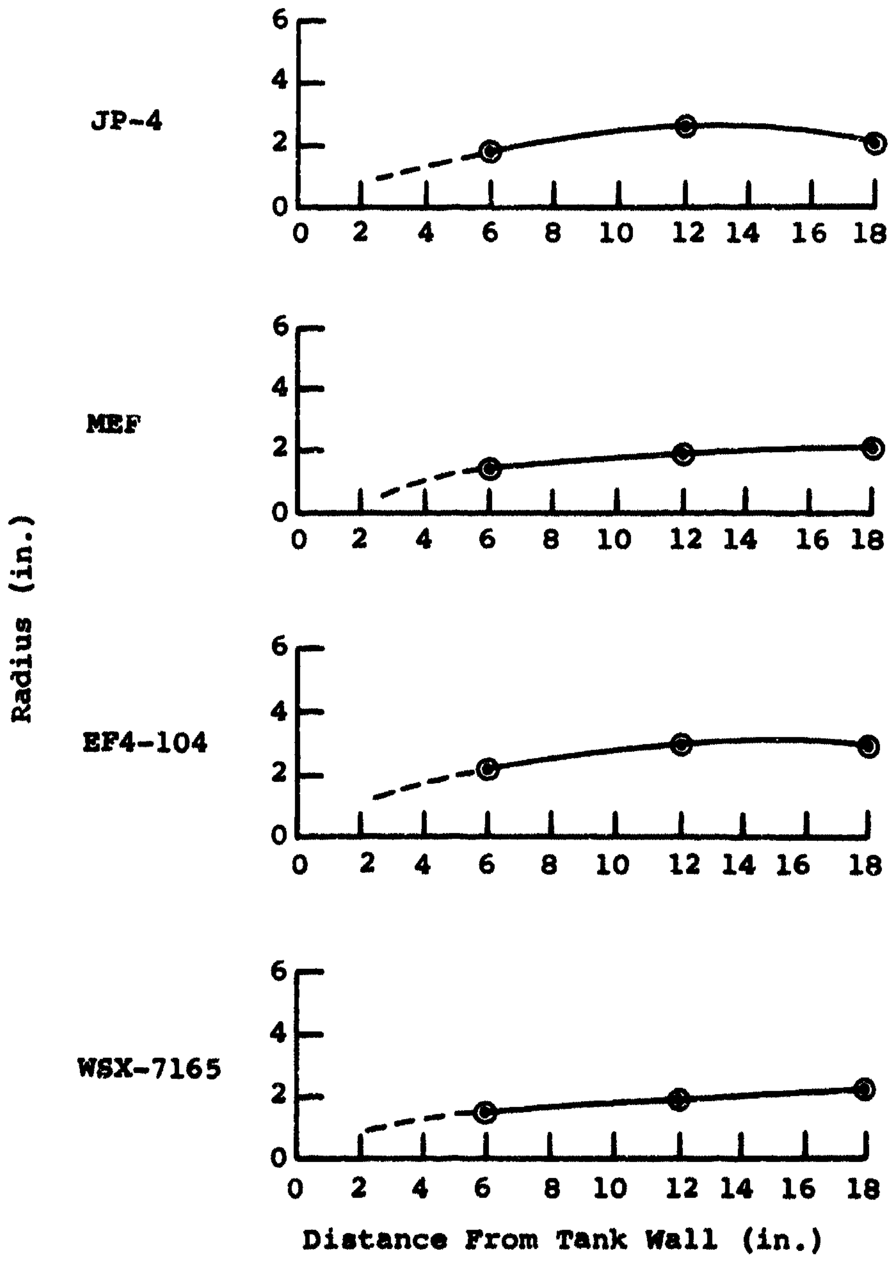


Figure 36. Fuel Spray Dispersion Patterns From Caliber .50 Ballistic Impacts on Conventional Self-Sealing Tank Panels.

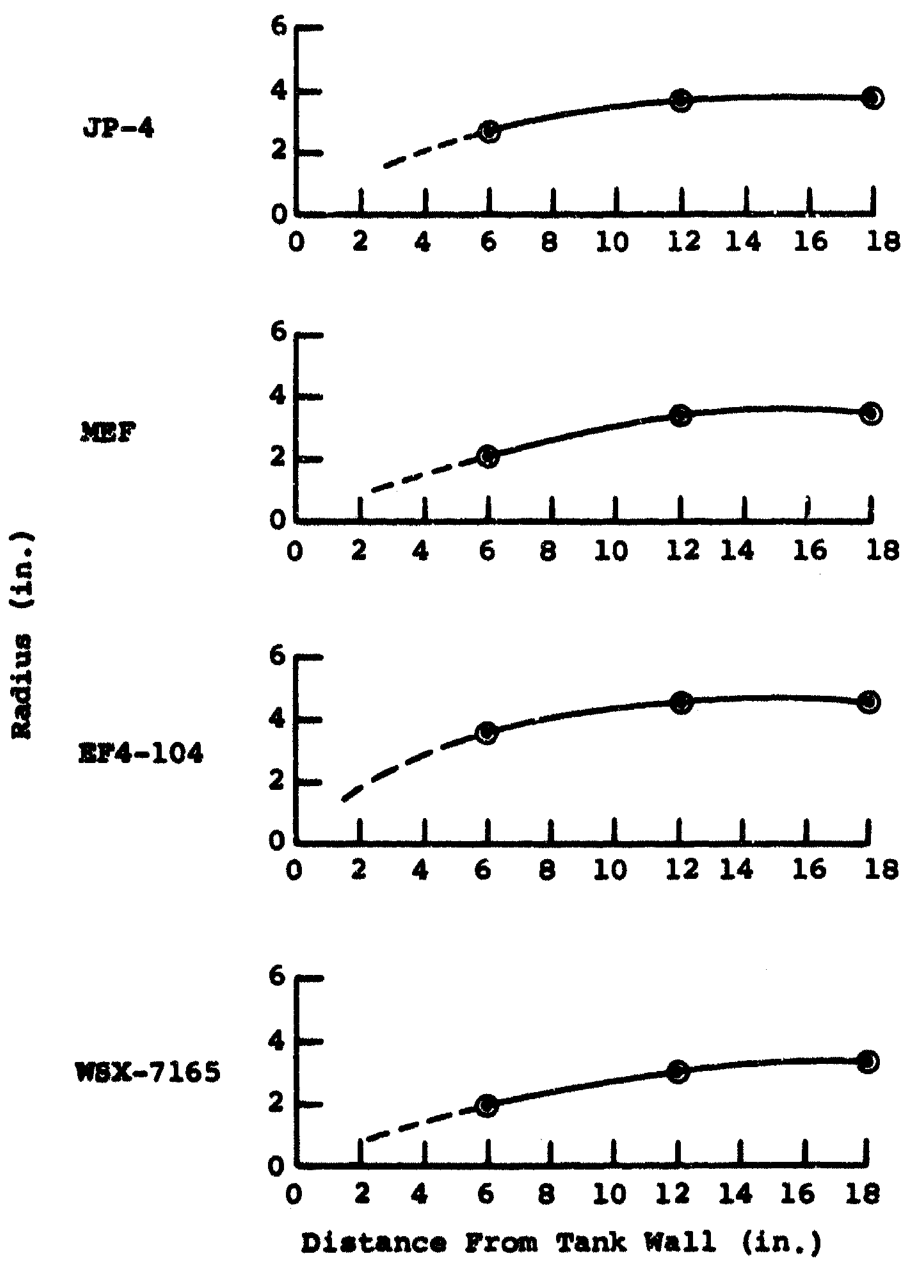


Figure 37. Fuel Spray Dispersion Patterns From Caliber .50 Ball'stic Impacts on Crash-Resistant Tank Panels.

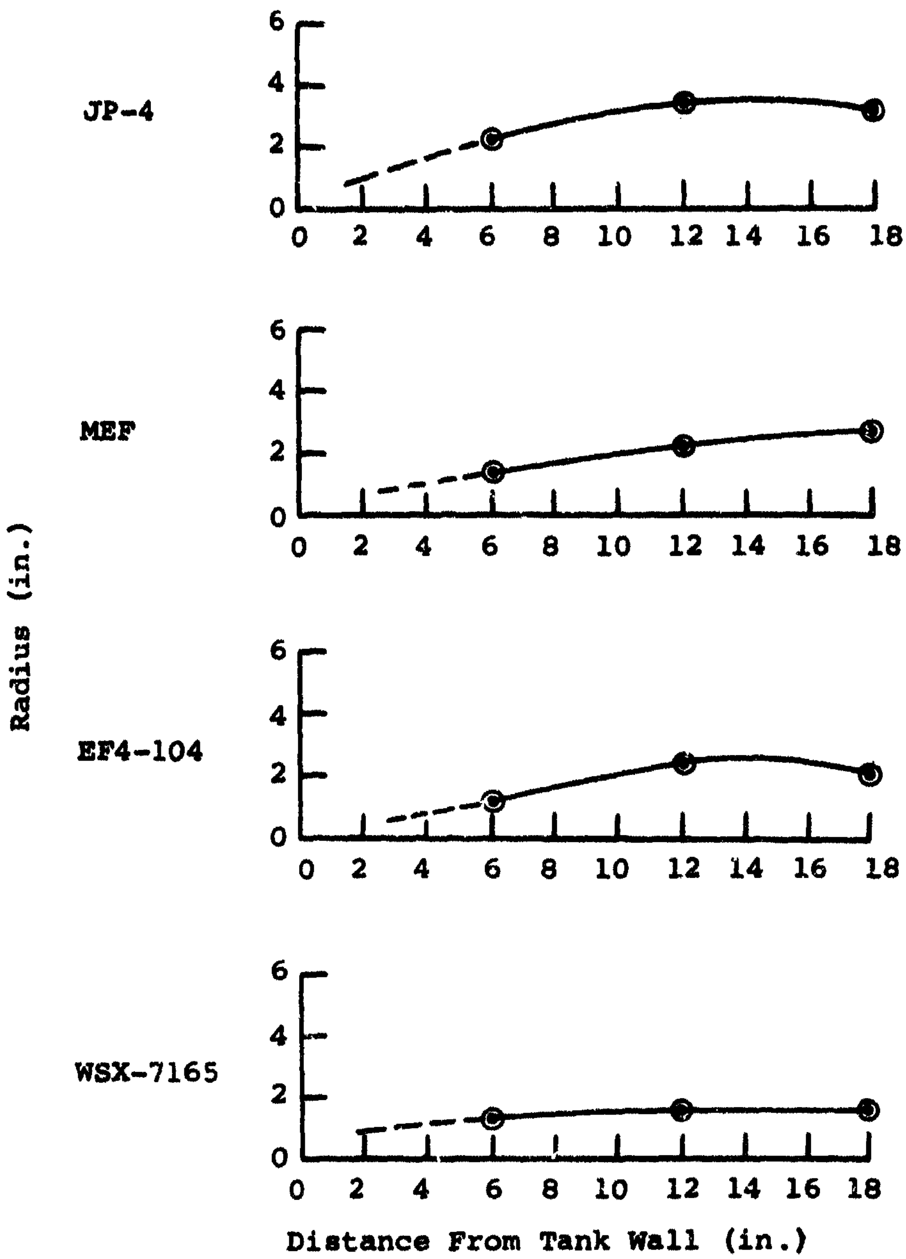


Figure 38. Fuel Spray Dispersion Patterns From Caliber .50 Ballistic Impacts on Coagulant Type Self-Sealing Tank Panels.

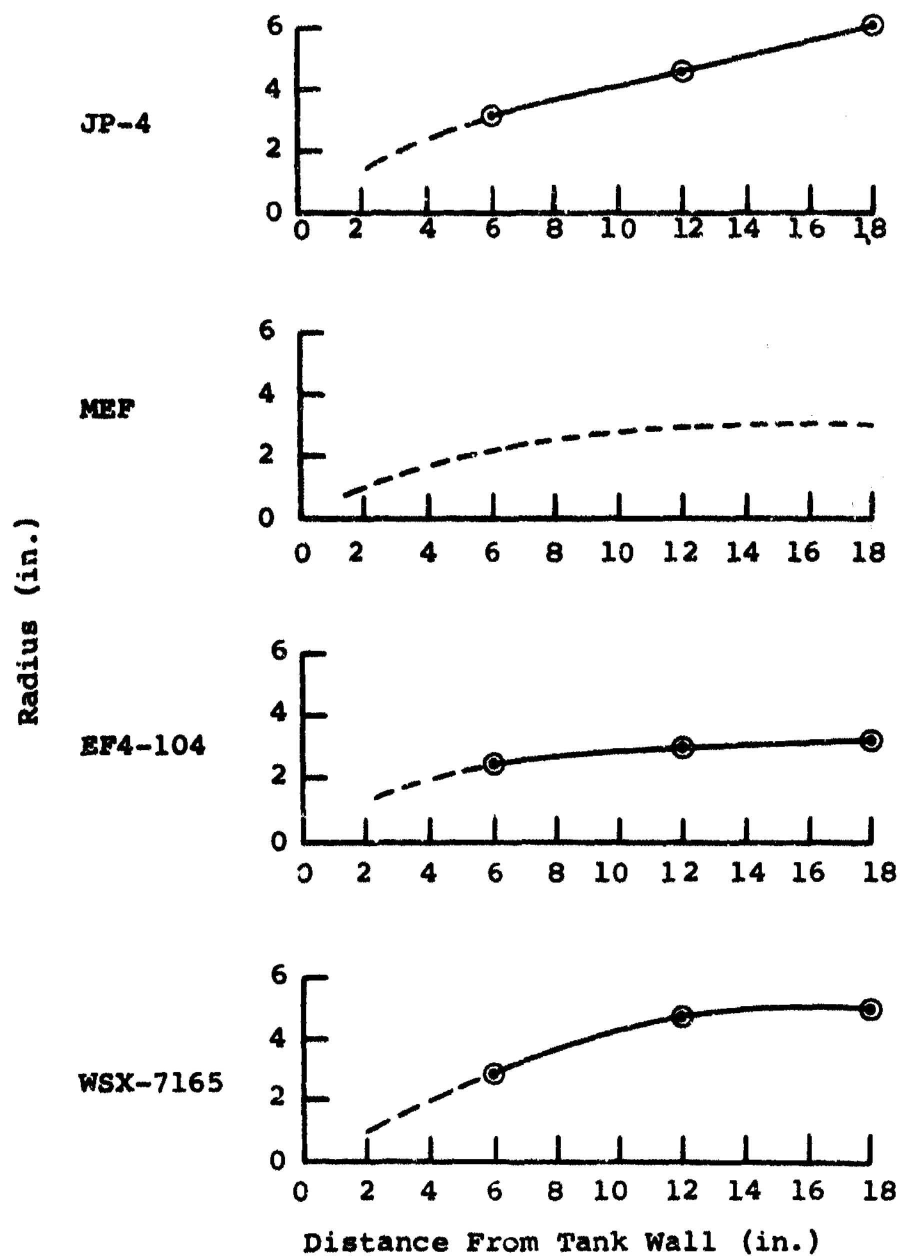


Figure 39. Fuel Spray Dispersion Patterns From 20 mm Ballistic Impacts on Conventional Self-Sealing Panels.

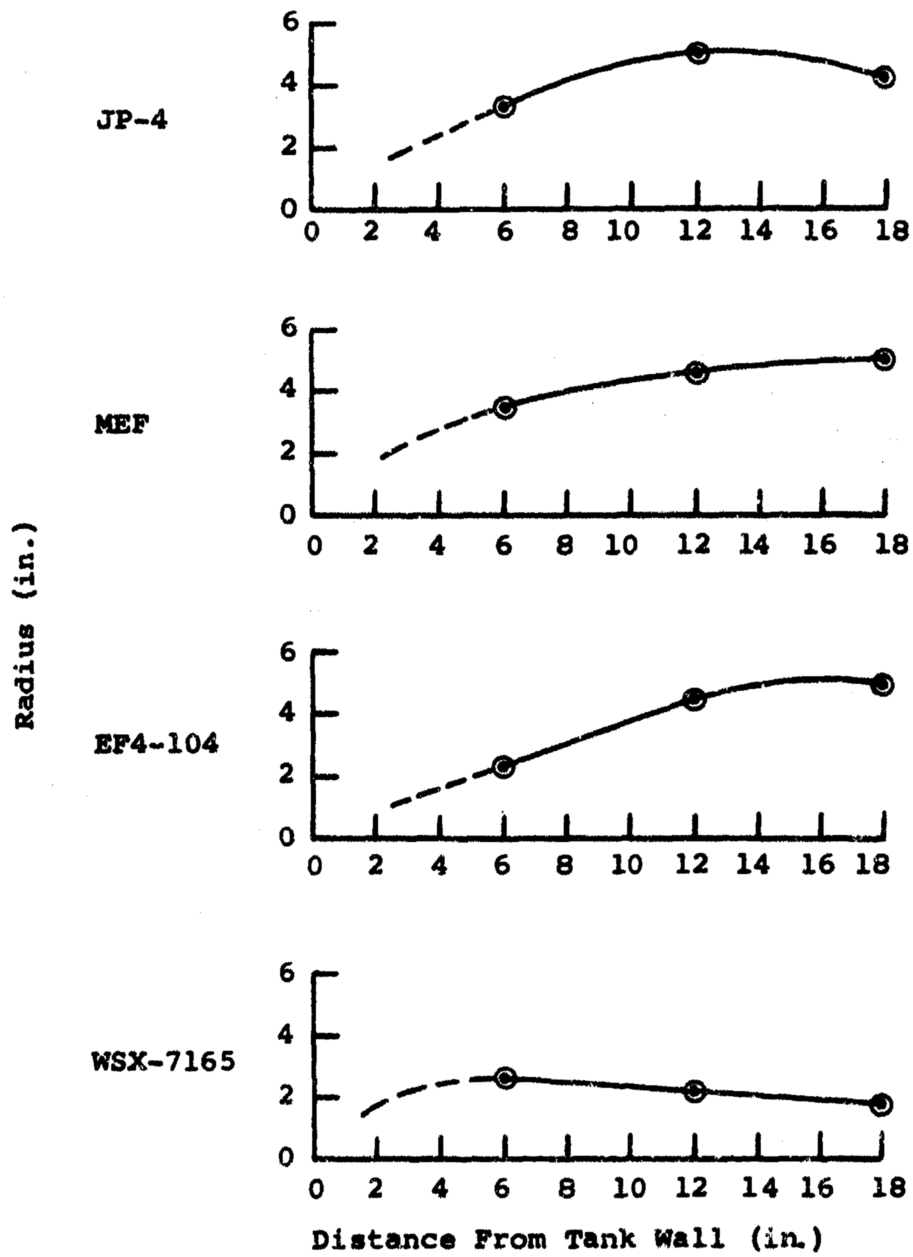


Figure 40. Fuel Spray Dispersion Patterns From 20 mm Ballistic Impacts on Coagulant Type Self-Sealing Tank Panels.

TABLE XI
THE DIMENSIONS OF FUEL SPRAY DISPERSIONS FOR TUMBLED CALIBER .50 BALLISTIC IMPACTS ON COAGULANT TYPE SELF-SEALING PANELS

Fuel Type	Spray Radius (in.) at Increasing Distances From the Tank Wall		
	6 inches	12 inches	18 inches
Liquid JP-4	6.9	8.4	9.5
MEF	5.7	7.4	8.4
EF4-104	4.5	6.4	8.0
WSX-7165	5.7	6.3	7.7

TABLE XII
THE DIMENSIONS OF FUEL SPRAY DISPERSIONS FOR TUMBLED CALIBER .50 BALLISTIC EXITS FROM COAGULANT TYPE SELF-SEALING PANELS

Fuel Type	Spray Radius (in.) at Increasing Distances From the Tank Wall		
	6 inches	12 inches	18 inches
Liquid JP-4	9.5	11.3	12+
MEF	8.6	9.2	11+
EF4-104	6.5	9.0	10.4
WSX-7165	7.5	9.6	11.6

This study of the dispersion of the test fuels under a variety of conditions has provided a great deal of quantitative data relative to their behavior. Generally, these data show some differences in the behavior of the emulsions when compared to liquid fuel, but the magnitude of the differences is often quite small. It must be concluded that other unique

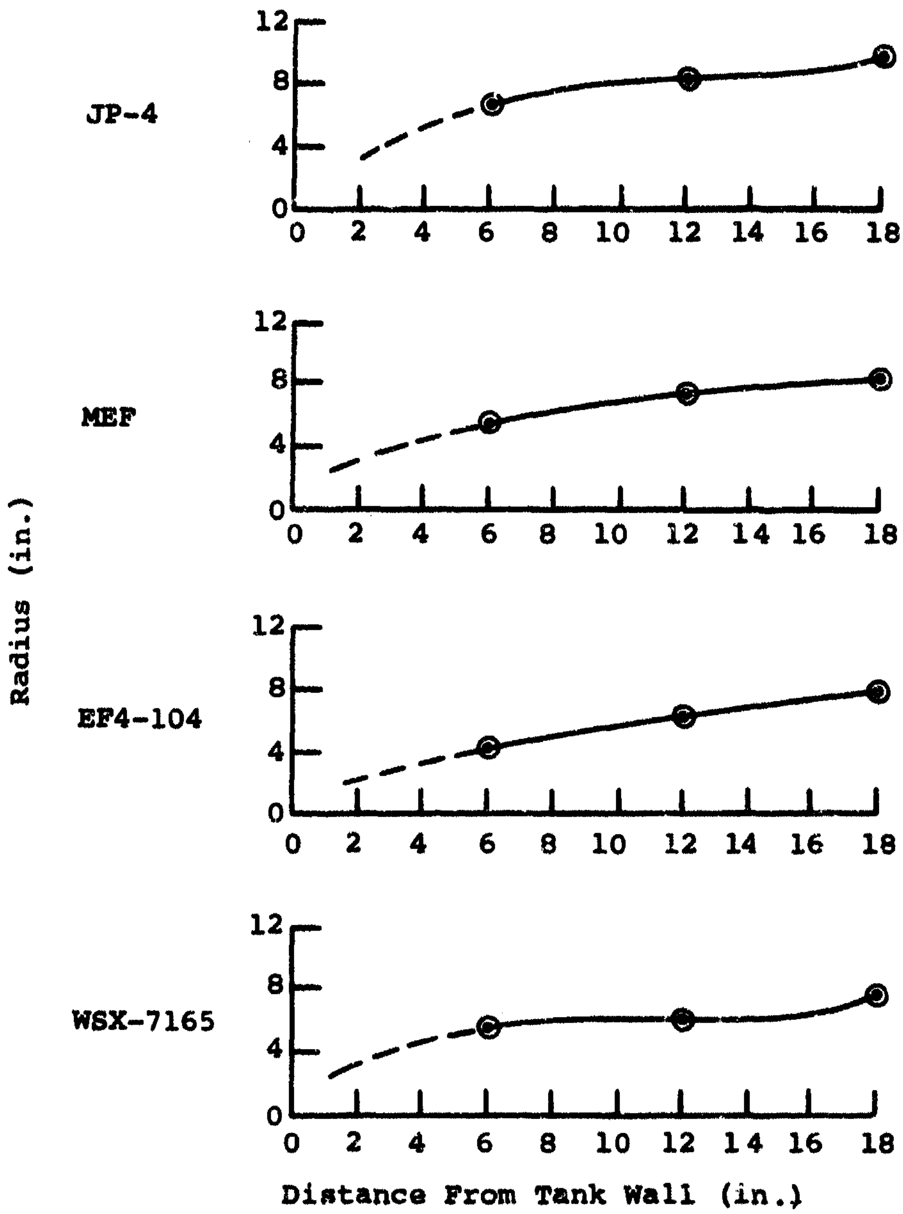


Figure 41. Fuel Spray Dispersion Patterns From Caliber .50 Tumbled Ballistic Entrance Hits on Coagulant Type Self-Sealing Panels.

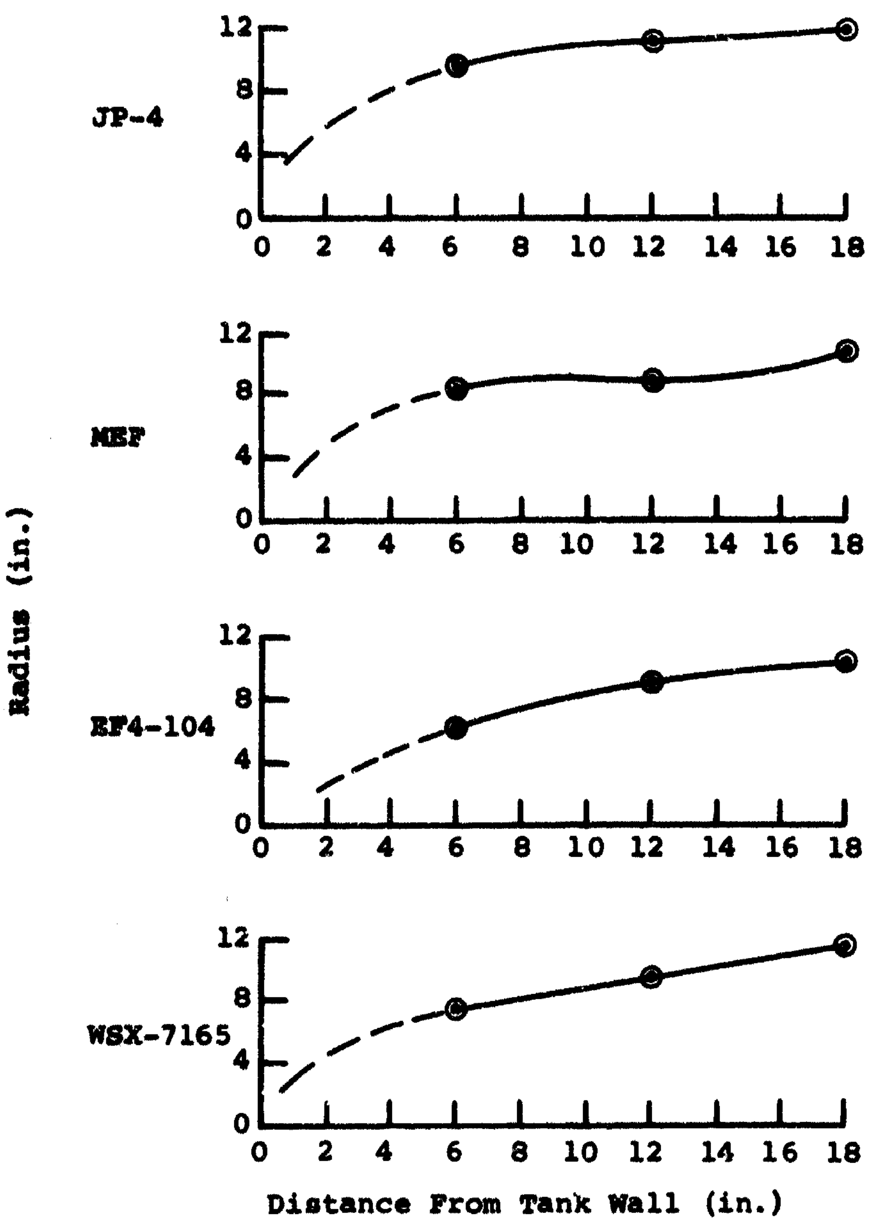


Figure 42. Fuel Spray Dispersion Patterns From Caliber .50 Tumbled Ballistic Exit Damage to Coagulant Type Self-Sealing Panels.

properties of the emulsified fuels will make a greater contribution to reduced aircraft vulnerability than can result from these modest reductions in spray dispersion dimensions under the high shear stresses of ballistic encounter.

V. FUEL IGNITION TESTS

Ignition is influenced by fuel volatility, droplet size, dispersion patterns, and a number of other parameters relating to the fuel, its environment, and the energy of the ignition source. To achieve fuel ignition, it is necessary to raise the temperature of a finite quantity of fuel and its immediate environment to a level where the heat released by the combustion reaction taking place can maintain the temperature of the reacting mass and can heat adjacent fuel layers to the required level. This process must take place in the environment of the fuel and ignitor. This means that a film of fuel on a metal plate will be more difficult to ignite than a similar film of fuel on a sheet of paper because of the high heat capacity and conductivity of the metal. It also means that a droplet of liquid fuel can extinguish a small ignition source, such as a hot metal particle, if it can cool the particle below the ignition temperature. Other examples might be given, but it is important to understand that a quantity of fuel plus an ignitor does not always produce a fire.

Four types of ignition sources were used in the several series of tests conducted in this program. These were:

1. An electric spark ignitor. This was a high-voltage, AC, continuous spark across the points of an automotive type spark plug.

2. Friction sparks. These were produced by the action of an 8-inch-diameter abrasive grinding wheel on a 3/8-inch hardened steel rod which had a 3/16-inch rod of a ferrocerium alloy (similar to lighter flint) in the center. These sparks were captured in a shield around the grinding wheel and released through a 1-inch spout. This produced a heavy stream of sparks which gradually expanded from the 1-inch diameter and could be thrown at least 2 or 3 feet.

3. Hot metal surface. This ignition source was a small "Calrod" type heating unit. It was 1/2 inch in diameter and 2-1/2 inches long. The temperature

of the surface could be varied by a change in applied voltage. The unit was heated to a bright red color before ignition tests. This produced a surface temperature of about 1200°F.

4. Incendiary bursts from API ammunition. Caliber .30 and caliber .50 rounds were functioned by firing the bullets through a series of aluminum target plates which were arranged in front of the test tanks. See Figure 43. Care was taken in each test to be certain that a good incendiary burst was produced in the region just in front of the fuel tank wall. When such bursts were not achieved, the tests were repeated. All tests were witnessed by an observer and a motion picture camera. The incendiary rounds used in the tests were caliber .30 M-14 API and caliber .50 M-8 API.

The types of fuel ignition tests which were performed in this part of the program followed closely the pattern of the fuel dispersion tests discussed in Section IV of this report. Thus, the tests included fuel drop ignition tests, BRL fuel nozzle spray ignition tests, and ballistic impact ignition tests with functioning API ammunition. Each of the four fuels was evaluated in each type of test with each of the planned ignition sources. In addition, the ballistic ignition tests had the added variable of three types of tank panel materials which were evaluated with each fuel. The detailed test plan for the performance of the various ignition tests is given in Appendix II.

A. FUEL DROP IGNITION TESTS

These tests were performed from the 20-foot drop height and employed 250 grams of fuel, just as the drop dispersion tests discussed in Section IV did. Figure 15 shows the arrangement of the test components, including the ignition source. Note that the ignitor was kept 4 inches above the concrete surface to prevent ignition of fuel which came to rest on the pad. The purpose of the tests was to evaluate the ignition properties of the fuel droplets produced by the impact as they moved out through the air. The fuel which remained on the surface of the pad could have been ignited by any of

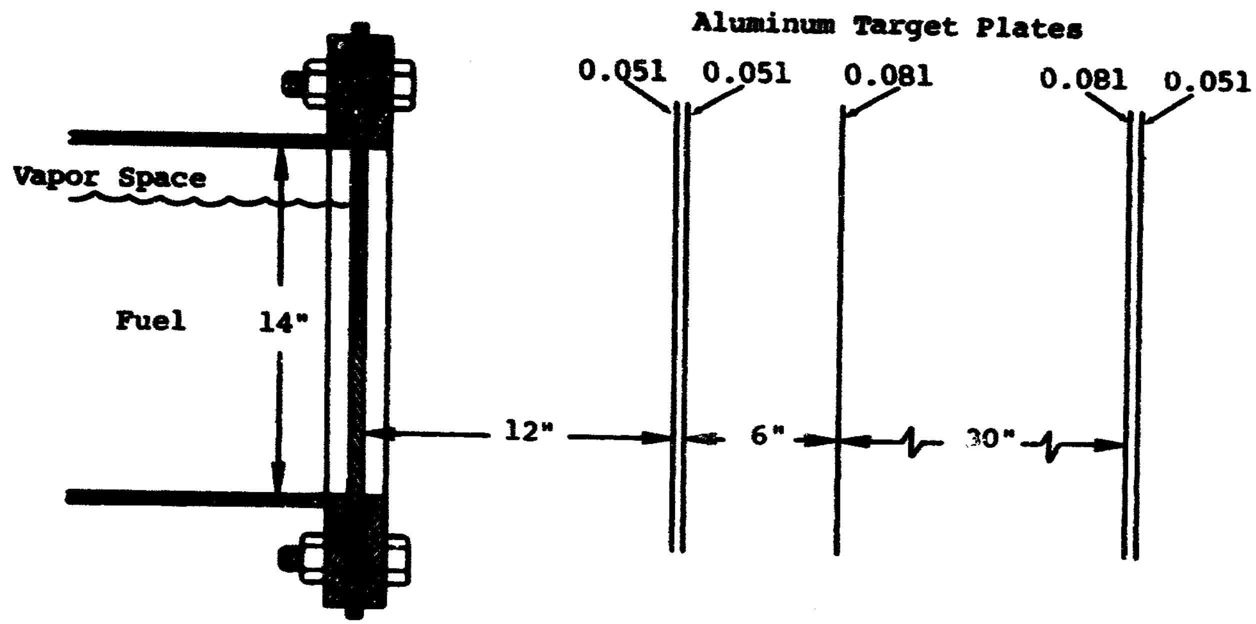


Figure 43. Arrangement of Test Components for Caliber .30 and Caliber .50 API Fuel Ignition Evaluation.

the ignition sources if plenty of time were allowed and the ignitor were lowered to the surface.

A region of probable ignition was defined for each combination of fuel and ignitor by increasing the distance between the drop point and the ignition source until a distance was reached where less than 50 percent ignitions occurred in a sample of five tests. Some ignitions propagated to a substantial quantity of fuel droplets and to the fuel on the surface while others did not. Any ignition which produced a visible flame at the ignition source, or beyond, was counted as an ignition. The tabulated results do not imply that a big fire was produced for every ignition, nor do they imply that ignitions are not possible beyond the probable ignition limit. Ignitions are possible to the full range through which fuel is scattered, but ignitions become very unlikely at the outer limits reached by fuel droplets.

Table XIII presents the probable ignition limit data which have been developed for the electric spark and hot metal surface ignition sources. These data clearly show that the liquid JP-4 fuel is more easily ignited than the emulsified fuels. It is also clear that this hot metal surface is a much stronger ignition source than the electric spark. It should be noted that the electric spark was very close to a point source, since the spark plug gap was less than 1/8 inch. The hot metal surface had a presented area of more than 1 square inch and also had a large reservoir of thermal energy, while the spark has almost no mass and thus very little stored energy for heating and vaporizing a fuel droplet.

A considerable number of ignition tests were performed at distances which were greater or less than the probable ignition limits reported. These data generally support the limits which are reported in Table XIII; thus, a detailed presentation of the additional tests will not be included in this report.

A number of drop ignition tests were performed using the friction spark ignitor. Figure 44 indicates the various ways that the spark stream was directed at or through the fuel dispersion. It was not possible to get the discharge port on this spark source closer to the drop surface than 6-1/2 inches because of the size and shape of the equipment

TABLE XIII
PROBABLE IGNITION LIMITS FOR FUELS DROPPED FROM A HEIGHT OF 20 FEET

Ignition Source	Fuel Type	Probable Ignition Radius (in.)	Supporting Test Results (ignitions/trials)
Electric Spark	Liquid JP-4	12	3/5 at 12 in. 1/5 at 15 in.
Electric Spark	MEF	None	0/5 at 4 in.*
Electric Spark	EF4-104	None	1/5 at 4 in.*
Electric Spark	WSX-7165	None	1/5 at 4 in.*
Hot Metal	Liquid JP-4	36	4/5 at 36 in. 2/5 at 42 in.
Hot Metal	MEF	18	4/5 at 18 in. 1/5 at 24 in.
Hot Metal	EF4-104	18	4/5 at 18 in. 2/5 at 24 in.
Hot Metal	WSX-7165	18	3/5 at 18 in. 1/5 at 24 in.

*It was not possible to locate an ignition source closer than 4 inches from the drop center without the fuel mass striking the ignitor as it fell.

used. The difference between this height and the 4-inch height used for the other ignitors is not considered to have significantly affected the ignition probability values for the friction spark tests.

The initial friction spark ignition tests were performed with the stream of sparks parallel to the surface, 6-1/2 inches above it, and offset from the drop center so that the point of closest approach of the spark stream would be

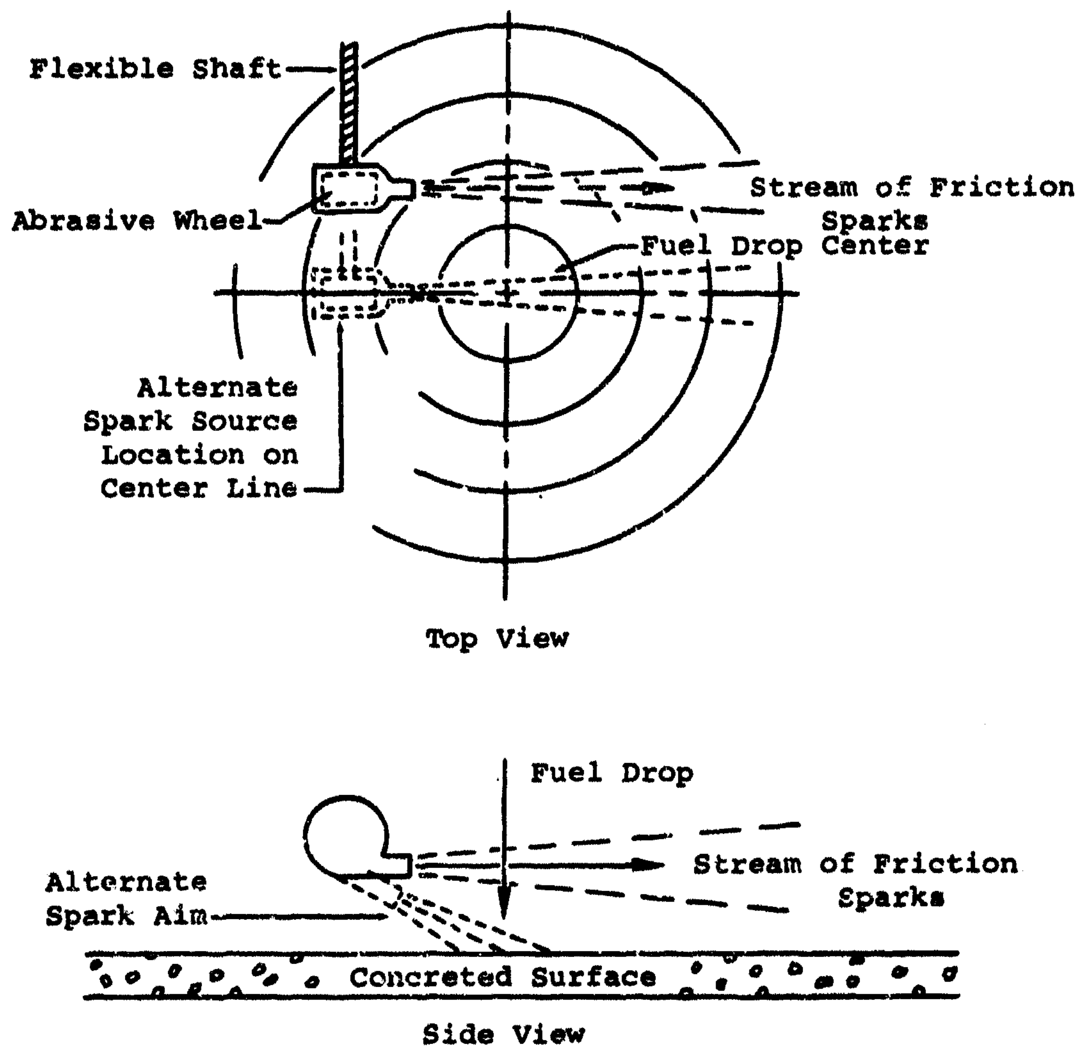


Figure 44. The Locations of the Friction Spark Ignition Source for Fuel Drop Ignition Tests.

approximately the equivalent of the ignition radius data developed for the other ignitors. No ignitions occurred with this test arrangement for any of the fuels. The discharge port on this spark source was 12 inches back from the drop center. After a number of tests without ignitions, the stream of sparks was moved to the alternate location shown in Figure 44 and was thrown through the center line of the fuel cloud but still above the flat surface and parallel to it. Table XIV presents the results of these tests. These data indicate that fuel droplet ignitions by

TABLE XIV
FRICTION SPARK IGNITION RESULTS FOR FUELS DROPPED FROM A HEIGHT OF 20 FEET

Fuel Type	Test Results* (ignitions/trials)
Liquid JP-4	1/5
MEF	0/5
EF4-104	1/5
WSX-7165	0/5

*All sparks were from 6-1/2 inches above the surface, parallel to the surface, 12 inches back from the drop center, and through the center line of the fuel cloud.

friction sparks are possible but not probable for any of these fuels.

As a further test of the ignitability of these fuels with friction sparks, the aim of the spark stream was changed so that the sparks struck the surface at the center point of the drop. This permitted the sparks to come in contact with the vaporizing fuel on the surface as well as the fuel droplets which were sprayed through the air. With this test arrangement, it was possible to get ignitions with all fuels on all tests. However, very long delays were frequently apparent between the time the fuel hit the surface and the time a fire started. This indicates that it was very frequently the layer of vaporizing fuel which was ignited by the friction sparks rather than droplets of liquid fuel.

B. BRL FUEL SPRAY IGNITION TESTS

The purpose of these tests was to define a region of ignition around the fuel spray for each fuel in combination with each ignition source. Thus, the tests serve to define the region through which fuel is sprayed and also to evaluate the response of the fuel to the ignitor.

Specific procedures used in conducting these tests are included in the test plan given in Appendix II. Figure 45 indicates the arrangement of the test equipment used. The BRL fuel nozzles were fired horizontally, and the ignitor was placed on a level with the nozzle and a measured distance out from it and to the side of its line of fire. Tests were performed with the ignition source 6, 12, and 18 inches away from the mouth of the fuel nozzle and at radii from 0 to 8 inches away from the spray axis. The ignition sources used were the same as discussed earlier in this section of the report.

Figures 46 and 47 show a typical test. In this instance, the hot-metal ignitor was 18 inches away from the nozzle mouth but on the center line of the spray where 100 percent ignitions occur. The fuel was liquid JP-4. Figure 46 shows the impact of part of the fuel spray with the ignitor but was taken prior to fuel ignition. Figure 47 was taken a moment later when the ignition had taken place and was spreading to the rest of the fuel, which was then well past the ignition source. Figures 48 and 49 present a graphical summary of the test results with the electric spark and hot metal ignition sources. Tables XV and XVI summarize the test data upon which the figures are based.

Two lines have been drawn on the plots in Figures 48 and 49. These indicate the radius from the spray axis where ignitions are very probable (nearly 100 percent) and the radius from the spray axis where ignitions are very improbable (nearly zero percent). At radial distances between these two lines, the probability of ignition decreases with increasing radius values.

It will be noted that the values for the ignition envelopes about the spray are in good agreement with the spray dispersion patterns presented earlier in Figure 30. The ignition radii tend to be somewhat greater than might be expected

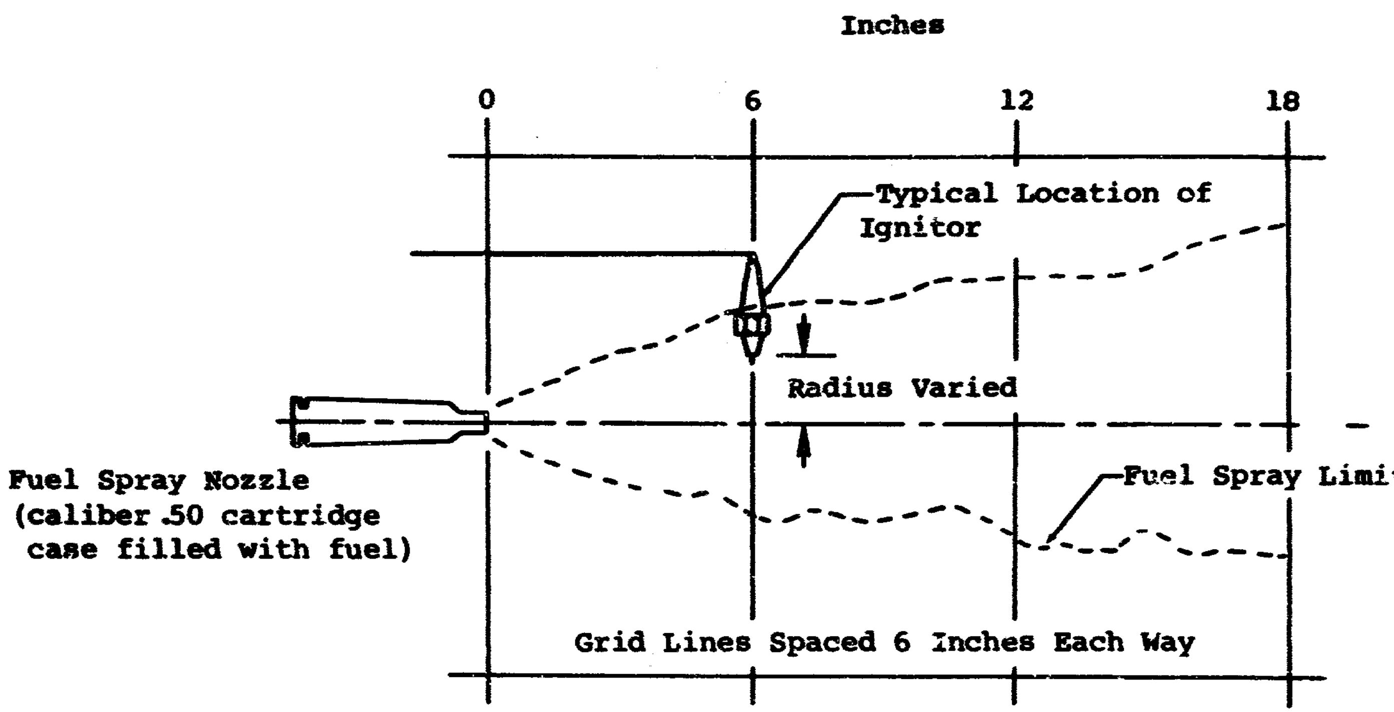


Figure 45. Arrangement of Test Components for BRL Fuel Spray Ignition Evaluation.

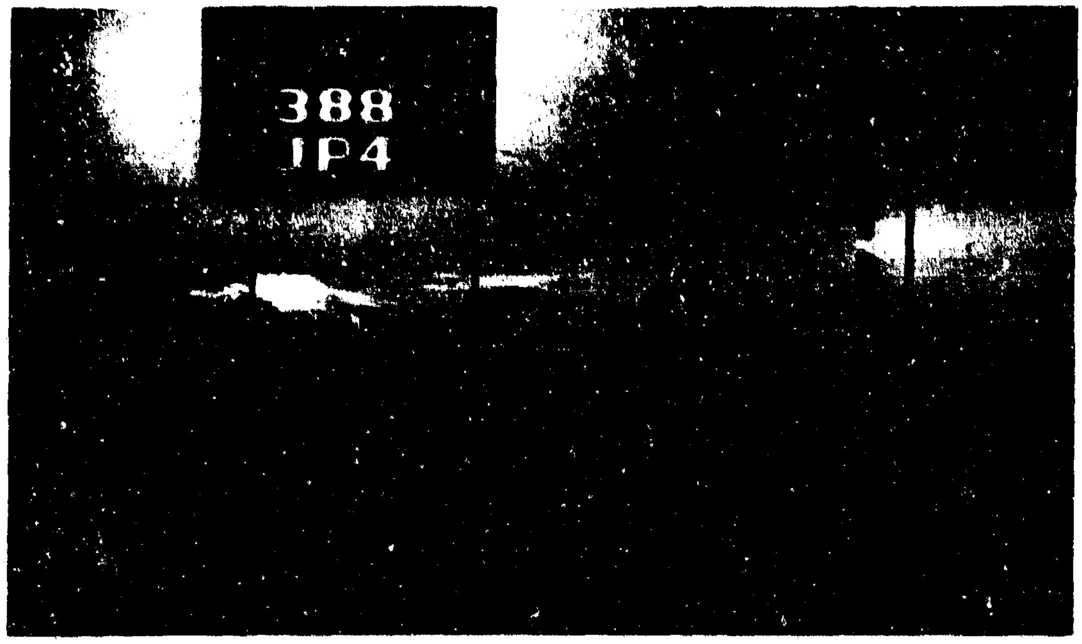


Figure 46. BRL Fuel Spray Ignition Test of Liquid JP-4 Just Prior to Ignition by a Hot Metal Surface.

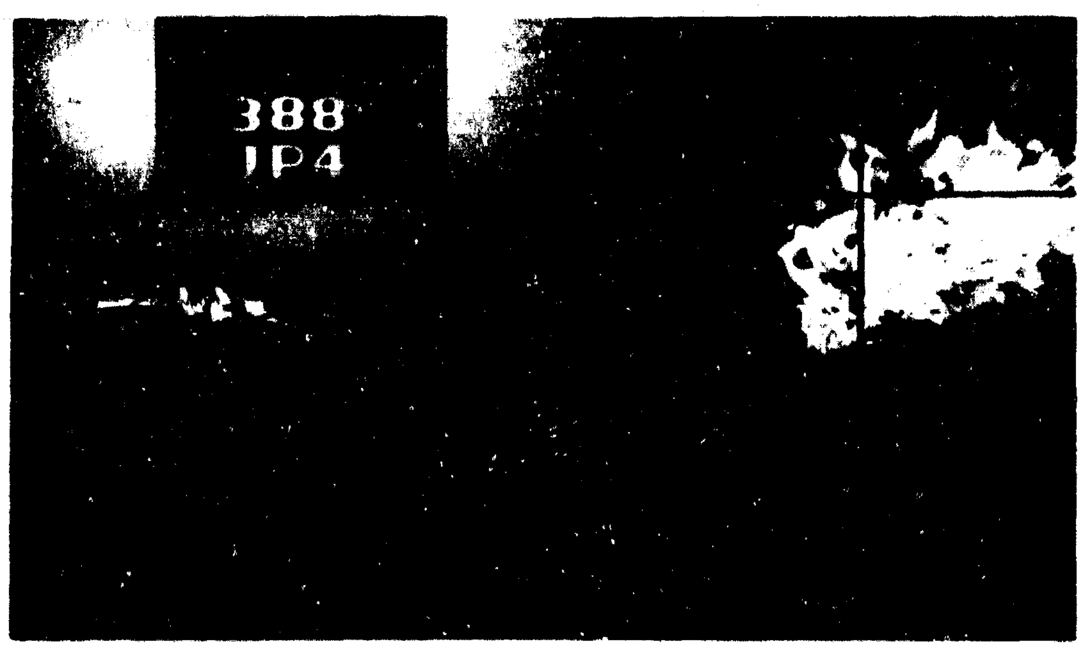


Figure 47. BRL Fuel Spray Ignition Test of Liquid JP-4 Just After Ignition by a Hot Metal Surface.

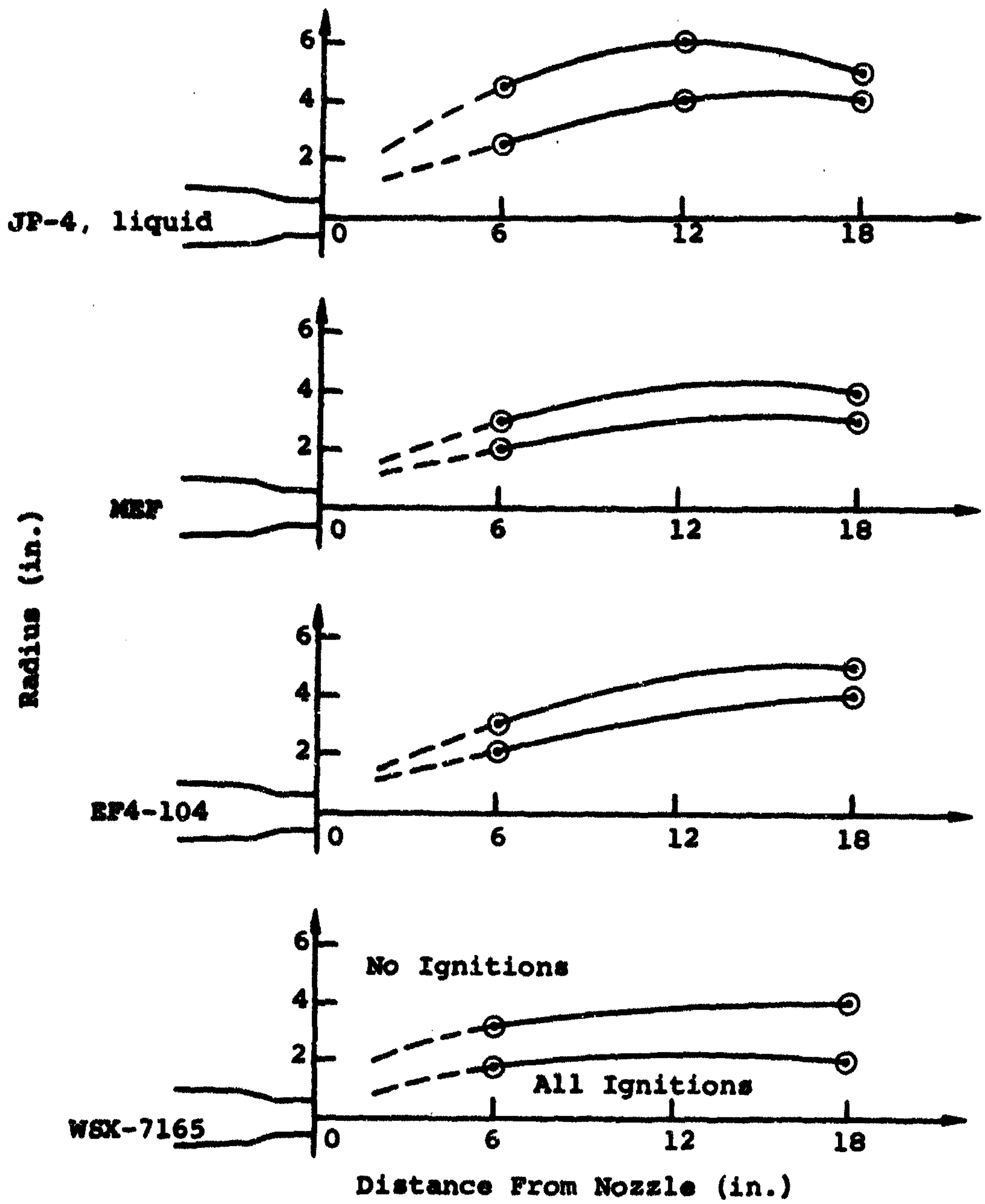


Figure 48. Regions of Fuel Spray Ignition by an Electric Spark.

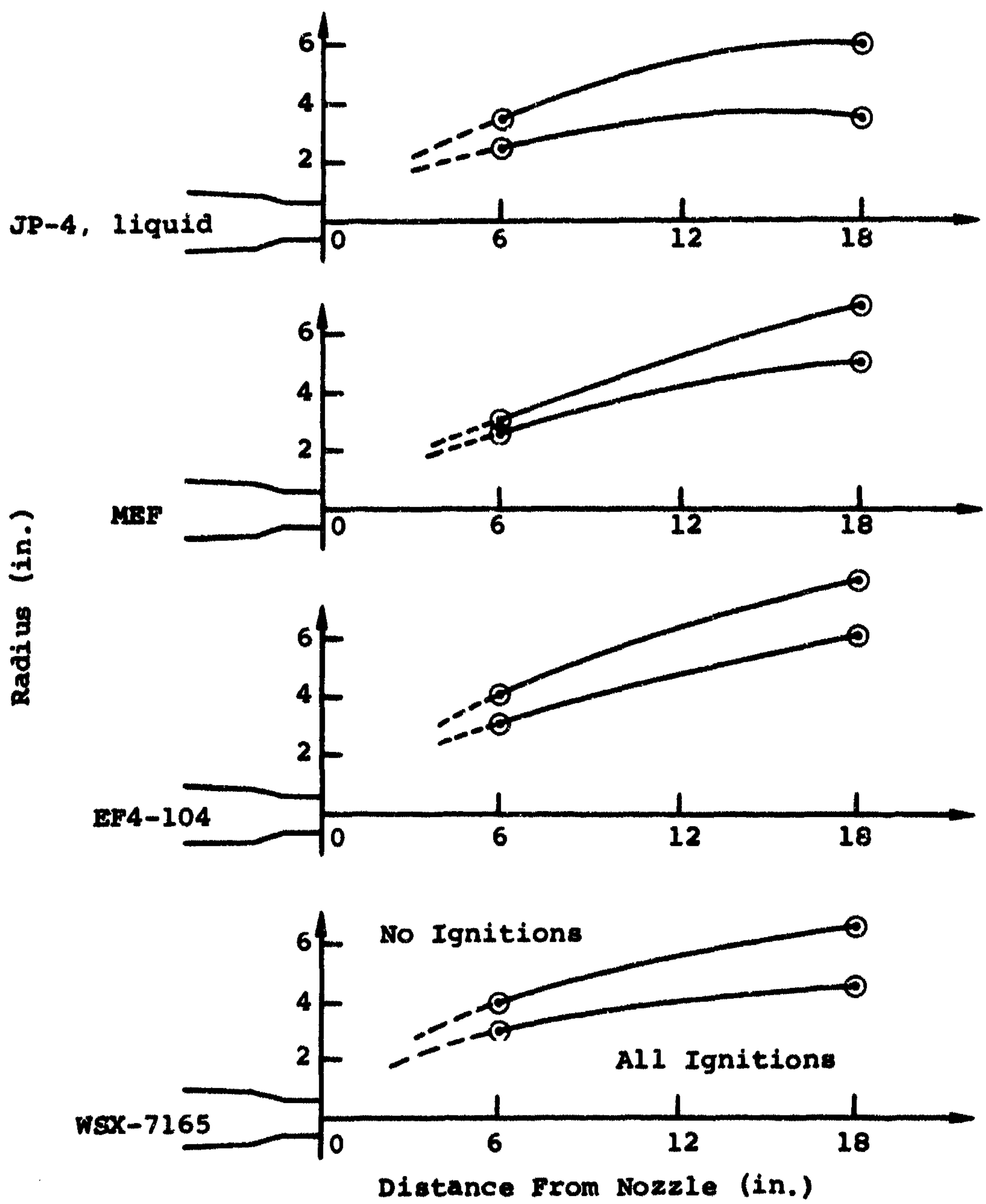


Figure 49. Regions of Fuel Spray Ignition by a Hot Metal Surface.

TABLE XV

BRL FUEL NOZZLE IGNITION TEST RESULTS WITH AN ELECTRIC SPARK IGNITOR

Fuel Type	Ignitor Location: Lineal (in.) From Nozzle	Ignitor Location: Radial (in.) From Spray Axis	Results (ignitions/ trials)
Liquid JP-4	6	2	5/5
	6	2½	1/1
	6	3	4/6
	6	3½	0/5
	6	4½	0/3
	12	4	5/5
	12	4½	3/6
	12	5	3/6
	12	6	0/5
	18	4	5/5
	18	5	1/5
MEF	6	2	4/6
	6	2½	2/5
	6	3	0/5
	18	3	4/5
	18	4	2/5
EF4-104	6	2	4/5
	6	2½	2/5
	6	3	1/5
	18	4	3/5
	18	5	1/5
WSX-7165	6	2	4/5
	6	3	1/5
	18	2	2/2
	18	3	3/5
	18	4	0/5

TABLE XVI
BRL FUEL NOZZLE IGNITION TESTS RESULTS WITH A HOT METAL SURFACE IGNITOR

Fuel Type	Ignitor Location: Lineal (in.) From Nozzle	Ignitor Location: Radial (in.) From Spray Axis	Results (ignitions/ trials)
Liquid JP-4	6	2½	5/5
	6	3	2/3
	6	3½	0/5
	18	3½	4/6
	18	4½	2/4
	18	5	1/3
	18	6	0/5
MEF	6	2½	5/7
	6	3	2/6
	18	5	5/5
	18	6	3/5
	18	7	0/5
EF4-104	6	3	4/5
	6	4	0/5
	18	6	5/5
	18	7	2/2
	18	8	0/5
WSX-7165	6	2	1/1
	6	3	4/5
	6	4	0/5
	18	3	2/2
	18	4	5/5
	18	5	2/5
	18	6	1/5

from the data of Figure 30. This seeming inconsistency can be readily explained. The spray from the nozzle deviated from a truly straight path to some extent on every test. In the analysis of the fuel dispersion photographs, the radial measurements were made from the true axis of the spray; in the ignition tests, the axis was assumed to be straight. This means that a portion of the radial distance between the all-ignition and the no-ignition lines must be attributed to random eccentricity of the spray axis.

The ignition limits for the liquid JP-4 are somewhat greater than for the emulsified fuels when the electric spark ignitor is used. This was not true for the hot metal surface ignitor. While the radial ignition differences are not great, it appears that the emulsified fuels produce some larger droplets in the spray and that these larger droplets are seldom ignited by the electric spark but are generally ignited by the hot metal surface.

In addition to these ignition tests with the electric spark and hot metal ignitors, a good many tests were performed with the friction spark ignition source. The spark stream, which was described earlier, was placed to throw the sparks vertically through the center of the spray from the BRL fuel nozzle. Repeated tests failed to produce an ignition with any fuel. Even aviation gasoline was not ignited in this test. Since no ignitions were achieved in this way, the spark stream was moved so that it was parallel to the axis of the nozzle and as nearly coaxial with it as possible. This produced streams of fuel droplets and sparks that intermingled and moved along together for several feet from the nozzle discharge. In spite of this longer exposure time, fuel ignitions were never achieved with this arrangement. These friction spark ignition tests indicate that it is quite difficult to start fuel fires with hot metal sparks where the fuel droplets are moving rapidly through the air and thus the fuel vapor layers are very thin. It is indicated that the ignition of fuel takes place in a region of mixed fuel vapor and air and that the friction sparks generally do not possess sufficient energy to vaporize liquid fuel droplets and create the needed mixture. An infinite number of ignition trials, like the ones which were performed, would be expected to produce an occasional ignition, but the probability of occurrence has been shown to be very low.

It must be concluded from the BRL fuel spray test results that the ignition properties of the emulsified fuel do not differ greatly from the ignition properties of sprayed liquid JP-4. While the differences, which have been defined, indicate a slight reduction in the ignition envelope for the semisolid fuels under some circumstances, the advantage is not great enough to indicate a significant reduction in aircraft fuel vulnerability as measured by the ignition response of fuel sprays alone.

C. FUEL IGNITION BY INCENDIARY AMMUNITION

The final type of fuel ignition testing performed in the program evaluated the ability of functioned incendiary rounds to ignite the fuel spray forced from tanks by ballistic impacts. The test tank and target used for this ignition source evaluation are shown in Figure 43. A vapor space of approximately 20 percent of the tank volume was left at the top of the tank when it was filled. This permitted a certain amount of energy absorption through fuel movement within the tank, but the test is somewhat more severe than tests against actual aircraft fuel tanks because of the rigidity of the steel tank. This test procedure was used because of the economies it affords, and it is believed that the test results achieved in these ballistic fuel ignition tests are not significantly different from the results that would have resulted from extensive firings against many thousands of dollars worth of aircraft tanks. This test method offered the additional advantage of comparative testing using the crash-resistant and coagulant type self-sealing panel materials which are not currently available in complete tanks.

The liquid JP-4 was pumped into the test tank. No pump was found to be available which could be used to move the WSX-7165 fuel into the tank without breaking a substantial amount of the emulsion. Perhaps 10 to 15 percent liquid resulted from pumping this fuel with the equipment available. Time did not permit an extensive study of the alternate pump types which might ultimately be used; thus, to insure the integrity of the test results, the semisolid fuels were shoveled into the tank. All fuels were placed in the test tank in the same way to insure uniformity in the test results, although it was possible to handle the MEF and EF4-104

emulsions through the pumps available without any great amount of liquification.

Early tests revealed some instances where an emulsion of greater shear strength resulted from pumping; sometimes a stiff emulsion plus a very small quantity of liquid resulted. These variations were attributed to differences of the fuels in the storage tanks, to temperature, or to shear conditions inadvertently introduced into the lines due to bullet and target fragments which occasionally became lodged in the constrictions. Because of these variations, pumping of emulsified fuels was abandoned after the early tests, and it is believed that the emulsions involved in the results reported were essentially "dry" and of a shear strength which was very close to the "as-shipped" property of the fuels.

It was noted that the WSX-7165 emulsion was "stiffer" than the other emulsions, although no attempt was made to measure this difference quantitatively. It should also be mentioned that the WSX-7165 emulsion was partly broken by the shear forces introduced as the bullet passed through the test tank. A significant amount of liquid fuel resulted from impacts on the WSX-7165 test tanks, but no such liquification was observed with the other fuel emulsions.

All tests were witnessed by both a competent observer and a 2,000-frame-per-second film record. Thus, there was substantially no chance for misunderstandings to occur relative to the location or quality of the incendiary burst or the initiation of a fuel fire. Figure 50 shows several frames from a typical film record.

The results of the ballistic ignition testing with caliber .30 M-14 API rounds are presented in Table XVII, and similar data for caliber .50 M-8 API tests are presented in Table XVIII. These test results leave no doubt that the incendiary bursts from API ammunition are capable of igniting the fuel sprays of all of the fuels tested under ballistic impact conditions.

It should not be concluded from these data that all hits of incendiary bullets on aircraft will produce fire or that all fuel fires are equal in intensity. The functioning sensitivity of incendiary ammunition is such that many aircraft

0 Time

1 Millisecond
After Impact

6 Milliseconds

11 Milliseconds

Figure 50. Caliber .50 API Ballistic Ignition Test of MEF Fuel Emulsion Confined by Crash-Resistant Panel Material.

TABLE XVII
IGNITION PERFORMANCE OF CALIBER .30 API AMMUNITION AGAINST CANDIDATE AIRCRAFT FUELS CONFINED BY THREE TYPES OF TANK MATERIAL

Run No.	Fuel Type	Tank Panel	Test Results	Remarks
527	Liquid JP-4	Conventional self-sealing	Fire	Continued leakage, no self-seal
504	MEF	Same as 527	Fire	Very little continued leakage
501	EF4-104	Same as 527	Fire	Slight continued leakage, no self-seal
506	WSX-7165	Same as 527	Fire	Very little continued leakage, no self-seal
526	Liquid JP-4	Crash-resistant	Fire	Continued leakage
505	MEF	Same as 526	Fire	Continued leakage
503	EF4-104	Same as 526	Fire	Continued leakage
507	WSX-7165	Same as 526	Fire	Slight leakage only
570	Liquid JP-4	New type self-sealing	Fire	Very little leakage in spite of 1¼" rip
567	MEF	Same as 570	Fire	No continued leakage but no coagulant seal
566	EF4-104	Same as 570	Fire	Same as 567
568	WSX-7165	Same as 570	Fire	Same as 567

TABLE XVIII
IGNITION PERFORMANCE OF CALIBER .50 API AMMUNITION AGAINST CANDIDATE AIRCRAFT FUELS CONFINED BY THREE TYPES OF TANK MATERIAL

Run No.	Fuel Type	Tank Panel	Test Results	Remarks
460	Liquid JP-4	Conventional self-sealing	Fire	Extensive leakage, no self-seal
461	MEF	Same as 460	Fire	Little leakage, no self-seal
462	EF4-104	Same as 460	Fire	Same as 461
521	WSX-7165	Same as 460	Fire	Very little leakage, no self-seal
524	Liquid JP-4	Crash-resistant	Fire	Heavy fuel leakage
522	MEF	Same as 524	Fire	Same as 524
523	EF4-104	Same as 524	Fire	Slight leakage continued
518	WSX-7165	Same as 524	Fire	Same as 523
547	Liquid JP-4	New type self-sealing	Fire	Same as 523
562	MEF	Same as 547	Fire	Continued leakage, no coagulant seal
562	EF4-104	Same as 547	Fire	Slight leakage continued, no coagulant seal
546	WSX-7165	Same as 547	Fire	No continued leakage, no coagulant seal

hits will not cause the round to burst at all, or perhaps the burst will not occur near the fuel tank. These hits will rarely cause fuel fires. When fires are caused, the fires resulting from impacts on fuel emulsions are substantially smaller and more easily extinguished than fires from hits on liquid JP-4. This is due to the reduced fuel leakage which was generally observed for the emulsified fuels, even when tank self-sealing action was not effective.

The reduced fuel leakage, and generally smaller fires produced with the emulsified fuels, together with earlier favorable fuel dispersion and ignition data indicates that there are probably marginal incendiary ignition conditions where fires could be prevented through the use of emulsified fuels.

VI. FIRE EXTINGUISHANT PERFORMANCE ON EMULSIFIED FUEL FIRES

A. DISCUSSION OF THE TESTS

The ease with which fuel fires can be controlled or extinguished is an important aspect of aircraft survivability in many crashes. This program has included a series of tests to evaluate the potential advantages of various extinguishants which may be used to control fires resulting from spilled fuel in survivable crashes.

These tests have sought to provide quantitative results to the maximum extent which is practical. The fuel quantity, fuel surface area, wind direction and velocity, and burn time after ignition were all held constant in establishing the "standard fire" for the evaluation of extinguishants. The total weight of extinguishant and the time of application to the closest second were also determined. This procedure permits the establishment of an average rate of application. Results of the tests will be reported in these terms.

The extinguishants tested against liquid JP-4 and the three emulsified fuels were the following:

1. water
2. water fog
3. CO_2
4. liquid foam
5. dry chemical
6. sand
7. air

The basic test arrangement is shown in Figure 51. The fire pan for these tests was of steel, 4 inches wide by 20 inches long by 1-3/4 inches deep. This provided 80 square inches of fire surface (.56 square foot). It was located so that the airflow was down the long axis of the pan. One thousand grams of fresh fuel were used for each test. This quantity of fuel filled the pan to a depth of about 1 inch. Solidified fuels were leveled before ignition of the fire as shown in Figure 52. A 3-minute burn period was allowed in each test prior to the application of the extinguishant. This allowed

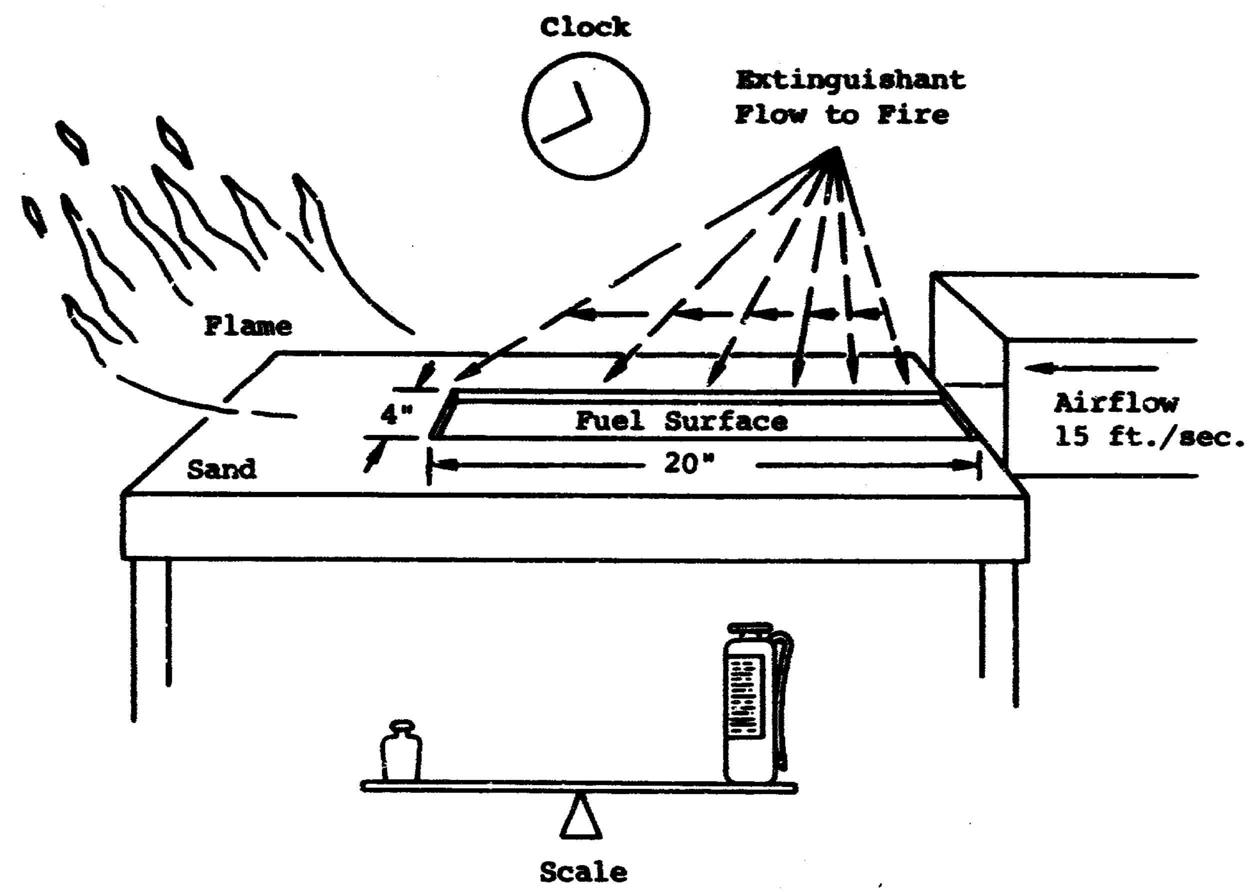


Figure 51. General Arrangement of Test Components for the Evaluation of the Fire Extinguishant Response of Emulsified Fuels.

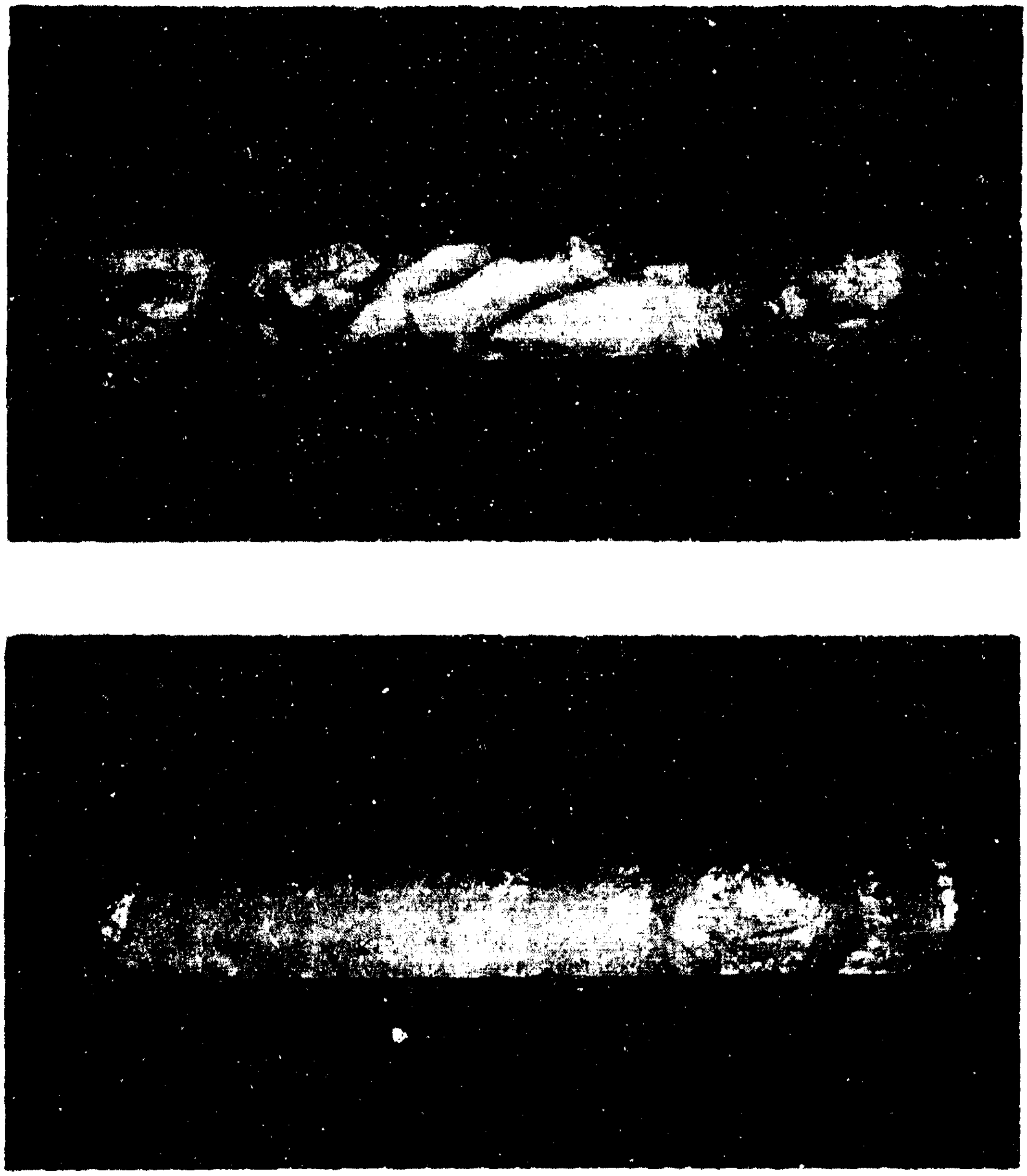


Figure 52. Emulsified Fuel as Placed in the Burn Pan (Above) and After Leveling (Below).

the fire to increase in intensity and to heat the pan, fuel, sand, etc., to a level which was at least partially representative of crash fire conditions.

The airflow over the fuel was adjusted to 15 feet per second, which is approximately equal to a 10-mile-per-hour wind. This condition increases the rate of fuel consumption substantially over a still air fire, but the fire intensity is not as great as may be encountered in many crashes where higher wind rates may be experienced. The unidirectional property of this airstream did assist the application of some extinguishing agents, since the wind could be depended upon to carry the agent on into the fire.

The fuel container was imbedded in sand, which absorbed the fuel which was spilled during the application of some extinguishants. The sand also provided a smooth and level surface around the fire. Thus, there were no flame holders or turbulence-inducing barriers in the fire region except for the fuel container itself (see Figures 53 and 54).

The fire extinguishants were applied at the lowest rates which were practical and yet still achieved fire extinguishment in a reasonable length of time (generally 5 to 60 seconds). This provided the best opportunity to evaluate differences between the fuels.

Many problems were encountered in achieving low flow rates with the extinguishing agents. Most fire extinguishing equipment is designed for very high application rates, and reducing the flow rate introduces a variety of problems. The methods of applying the extinguishants will be described more completely in the paragraphs which discuss the individual tests.

The order of extinguishant effectiveness, considering both the application rate and the time to extinguish the fire, was as follows:

1. dry chemical
2. CO_2
3. water fog
4. liquid foam
5. sand

Figure 53. Emulsified Fuel Fire Immediately After Ignition.

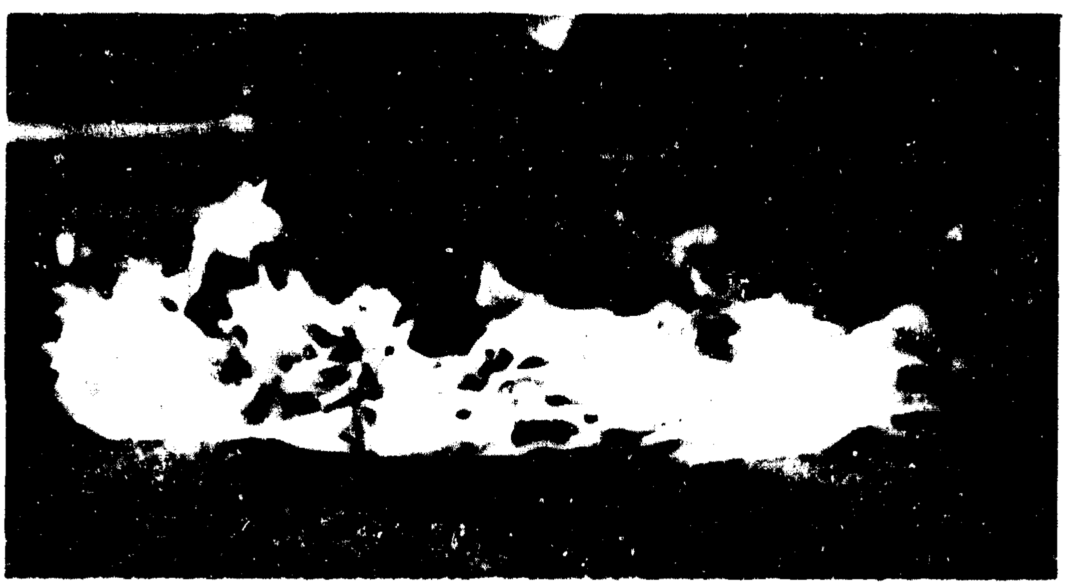


Figure 54. End View of the Standard Fuel Fire (3 Minutes Burn Time) Looking Into the Airstream.

6. water
7. air

Emulsified fuel fires were extinguished with all agents although only the first five listed are believed to be practical extinguishants. In the case of liquid JP-4, extinguishment was achieved with all agents except water which was not effective under these test conditions against a liquid fuel. The specific tests will be discussed in the order of extinguishant effectiveness.

B. DRY CHEMICAL EXTINGUISHANT

The dry chemical extinguishant used was a siliconized mono-ammonium phosphate powder which is normally expelled by air pressure and is approved for use against class A, B, and C fires. This material is as effective as any dry chemical which is presently commercially available for this use. It was not possible to control the flow rate from a dry chemical extinguisher below a rate of about 50 grams per second. Used by a skillful operator, this rate was capable of an almost instantaneous extinguishing action against the test fires. A variety of application techniques were subsequently tried in an effort to find a simple but controllable method of applying the powder at a rate of less than 5 grams per second. The best results were achieved with a simple hand-operated insecticide duster as shown in Figures 55 and 56. Average rates of about 3 grams per second (± 1.5 gr./sec.) were practical with this equipment. This agent was most effective when directed into the flame at the upwind side of the fire rather than onto the fuel. Clearly, this chemical does not "smother" or "blanket" the fire to accomplish the extinguishing action. Table XIX presents the results of the tests conducted. Each value is an average from at least three tests.

The variations in the test results are within the experimental accuracy of the tests. This chemical was highly effective against test fires with all four fuels.

Figure 55. Standard Fuel Fire Just Prior to Extinguishment With Dry Chemical Agent.

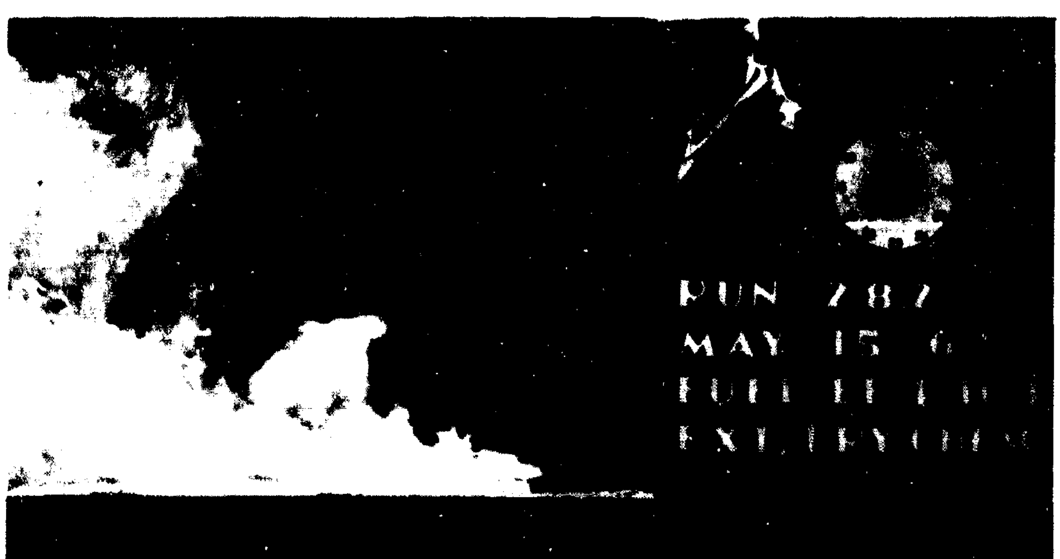


Figure 56. Application of Dry Chemical Extinguishant to the Standard Fuel Fire.

TABLE XIX
DRY CHEMICAL EXTINGUISHANT PERFORMANCE AGAINST JP-4 AND EMULSIFIED FUELS

Fuel Type	JP-4	MEF	EF4-104	WSX-7165
Application Rate (gr./sec.)	2.9	2.5	2.0	2.5
Time to extinguish (sec.)	5	4	6	4
Total agent applied (gr.)	13	10	12	11
Equivalent agent per unit of fire surface (lb./ft.^{2})	.05	.04	.05	.04

C. CARBON DIOXIDE EXTINGUISHANT

The carbon dioxide extinguishant was applied from a standard CO_2 extinguisher as shown in Figures 57 and 58. The CO_2 is stored as a liquid under high pressure in these units. The adiabatic expansion which takes place as the liquid CO_2 passes through the nozzle reduces the temperature of the stream to a level at which a mixture of gaseous and solid CO_2 is discharged. Thus, the standard CO_2 extinguisher is designed to accommodate the flow of large quantities of solid CO_2 "snow". At reduced flow rates, this "snow" tends to plug the nozzle and produce flow which is not entirely steady. The lowest average application rate for CO_2 which was found to be feasible was 15 grams per second ($\pm$ 4 grams per second). This rate was a satisfactory one, although a somewhat lower rate would have probably been sufficient to extinguish the test fire. Operator skill is a factor in the use of this extinguishing agent. It was important to direct the CO_2 at the upwind end of the fire and then progress downwind without permitting a flashback or reignition of fuel vapors which continued to flow from the extinguished fuel surface. Table XX presents the results of the tests conducted with CO_2. These values are averages of at least three tests in each instance. The apparent

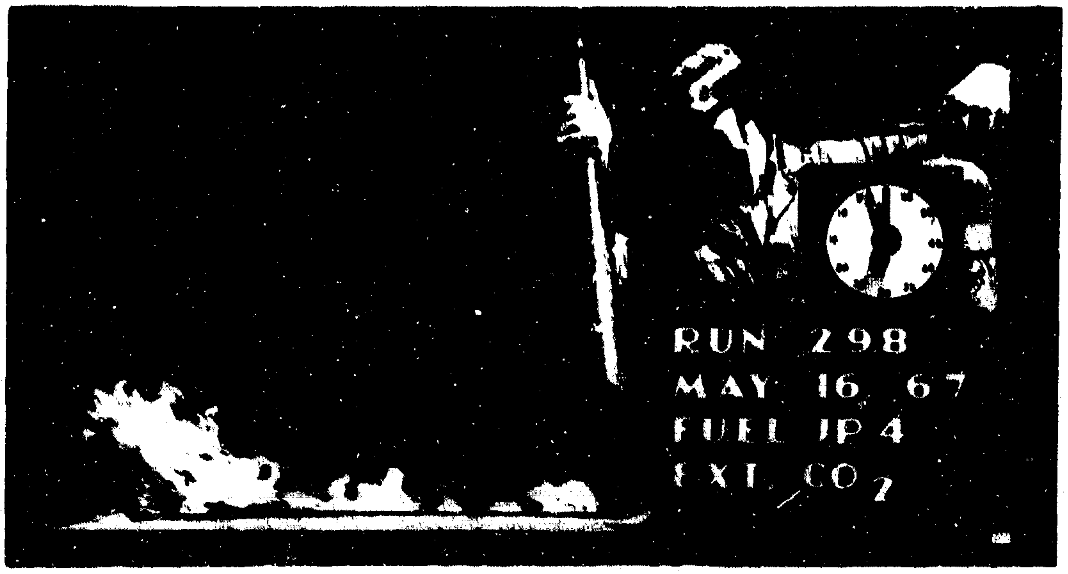


Figure 57. Standard Fuel Fire Just Prior to Extinguishment With CO_2.

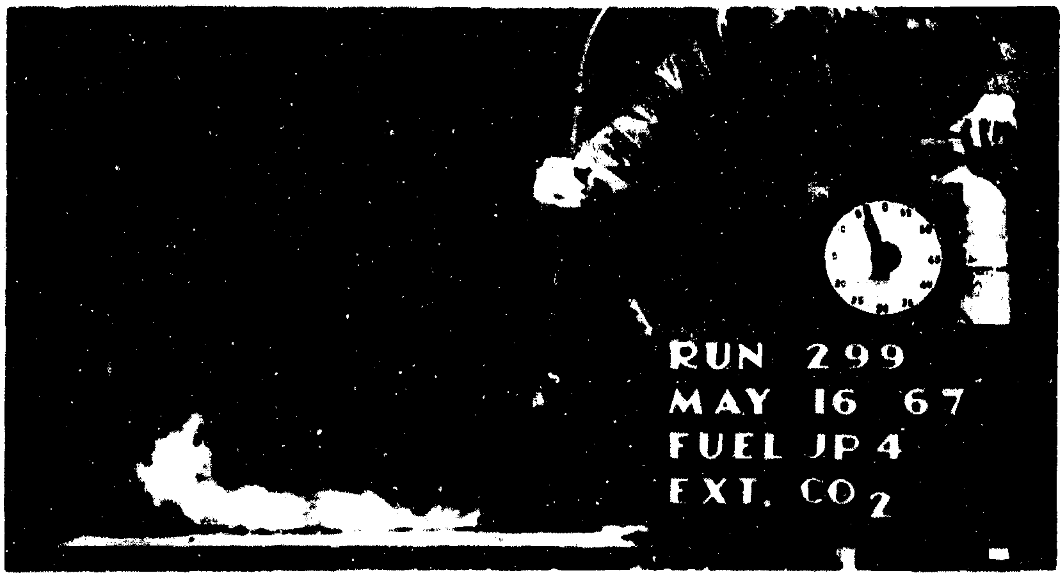


Figure 58. Application of CO_2 Extinguishant to the Standard Fuel Fire.

TABLE XX
CO_2 EXTINGUISHANT PERFORMANCE AGAINST JP-4 AND EMULSIFIED FUELS

Fuel Type	JP-4	MEF	EF4-104	WSX-7165
Application rate (gr./sec.)	18	15	12	16
Time to Extinguish (sec.)	4	6	6	5
Total agent applied (gr.)	76	87	74	74
Equivalent agent per unit of fire surface (lb./ft.^{2})	.30	.35	.29	.29

differences between results with the three fuels are within the accuracy of the tests. CO_2 was an effective extinguishant against all four types of fuel fires.

D. WATER FOG EXTINGUISHANT

A number of types of fog-producing equipment were tested in an effort to produce the very fine spray of a fog nozzle at a flow rate which was appropriate for the test fire. This equipment included a special fog nozzle for use in fire fighting, several types of high-pressure sprayers, and a paint sprayer which atomizes the water in a high-velocity airstream. The substantial flow of air with the fog also produced an effect on the fire which tended to confuse the effectiveness of the fog alone. Thus, the air atomization approach was not used, even though it produced the smallest fog particle size and the most control over the flow rate. The fog extinguishing tests reported here were accomplished using an air-pressurized insecticide sprayer as shown in Figures 59 and 60. This sprayer was set to produce the finest droplet size. The tests were run at an average flow rate of 8 grams per second (± 1 gram per second). Table XXI presents the results achieved with this water fog.

Figure 59. Standard Fuel Fire Just Prior to Extinguishment With Water Fog.

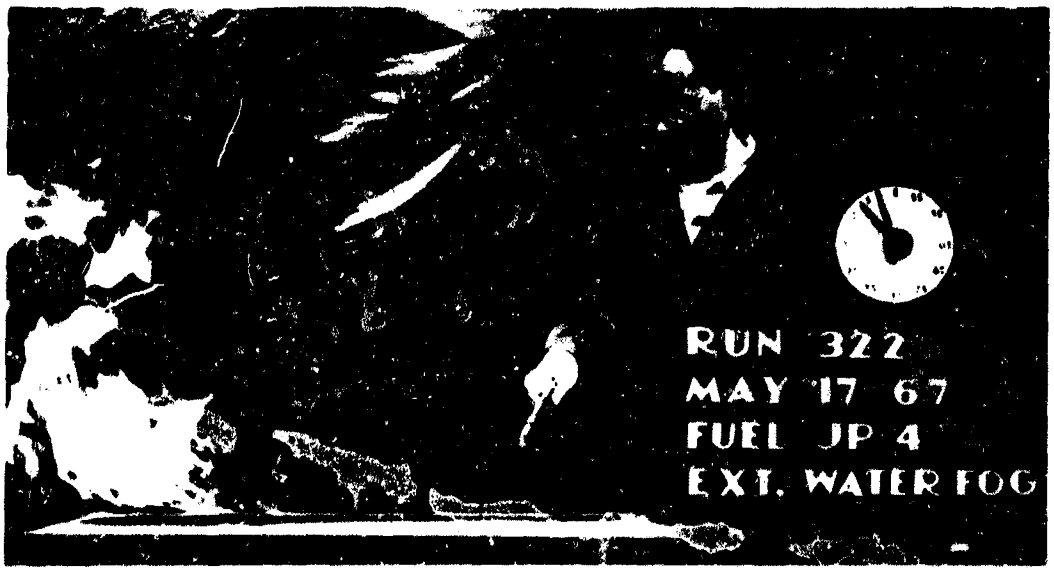


Figure 60. Application of Water Fog to the Standard Fuel Fire.

TABLE XXI
WATER FOG EXTINGUISHANT PERFORMANCE AGAINST JP-4 AND EMULSIFIED FUELS

Fuel Type	JP-4	MEF	EF4-104	WSX-7165
Application rate (gr./sec.)	8	9	8	8
Time to extinguish (sec.)	18	11	6	4
Total agent applied (gr.)	150	91	45	32
Equivalent agent per unit of fire surface (lb./ft.^{2})	.60	.36	.18	.13

These differences are substantially greater than the variation between individual tests. It must therefore be concluded that the emulsified fuel fires are more easily and more rapidly extinguished with water fog than is liquid JP-4. Further, the fires involving EF4-104 and WSX-7165 emulsions are more readily extinguished with water fog than are fires involving the MEF emulsion.

E. LIQUID FOAM EXTINGUISHANT

The liquid foam extinguishant employed in these tests was a water-based chemical foam type applied from a 2-1/2-gallon "Pyrene" foam fire extinguisher as shown in Figures 61 and 62. This unit is rated for use against class A and class B fires. The extinguishant flow rate is a function of the extinguisher size, but some control over the application rate for foam placed on the fire was achieved by placing a "Y" in the foam hose and regulating the flow in the bypass line. This type of chemical foam extinguisher is effective against certain types of fires, but the quality and flow rate of the foam produced varies from run to run and within individual runs to a considerable degree. The foam formation process is controlled by the way in which the two foam-producing solutions mix after the extinguisher is inverted. The

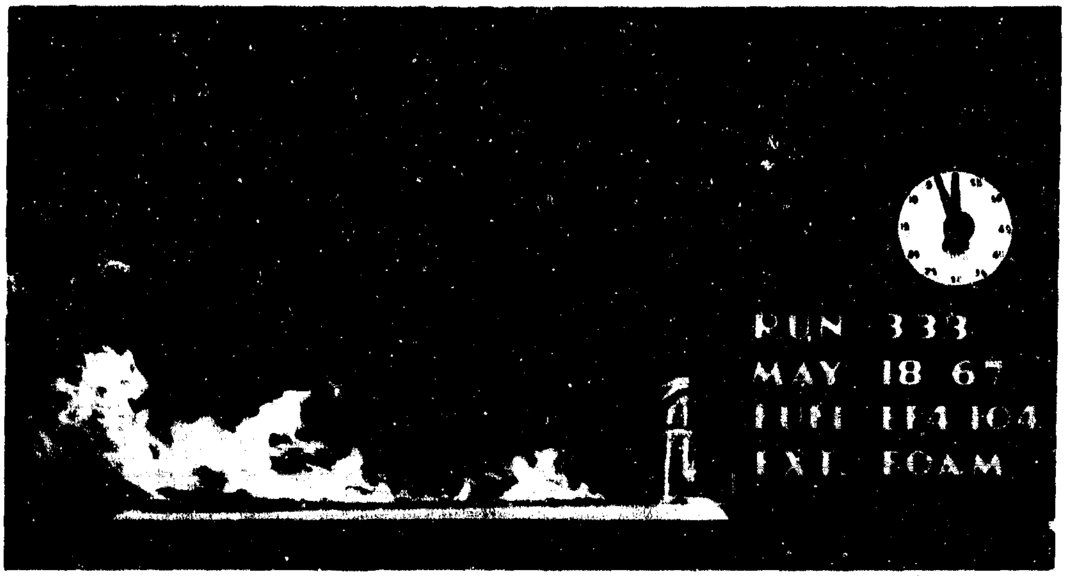


Figure 61. Standard Fuel Fire Just Prior to Extinguishment With Liquid Foam.

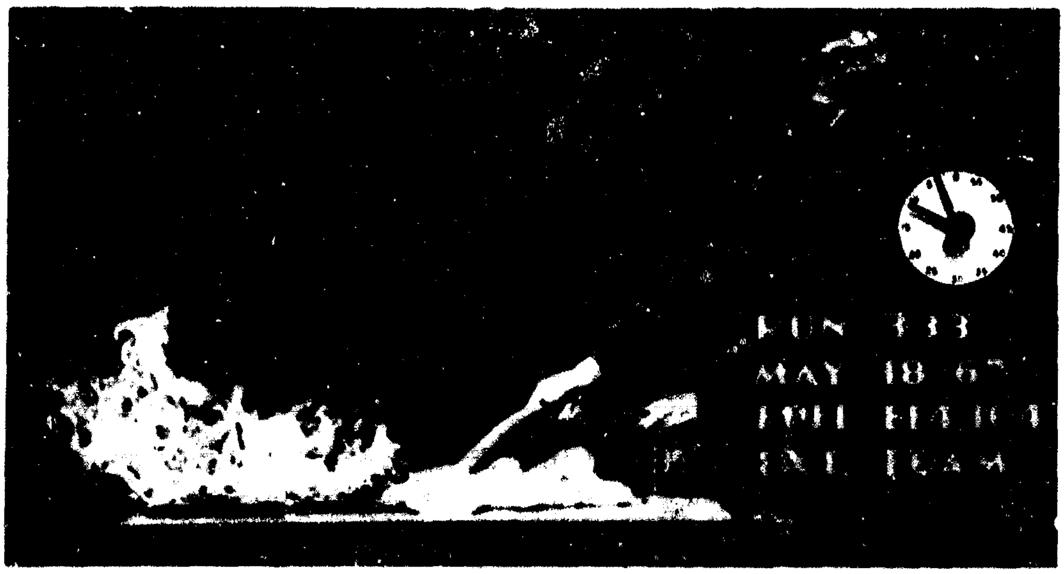


Figure 62. Application of Liquid Foam to the Standard Fuel Fire.

initial discharge from the extinguisher is nearly a liquid stream. As the foam generation process continues, the expansion ratio of the foam appears to increase but the volumetric rate of flow decreases. The initial discharge (for 2-5 seconds) was not applied to the fire so that the foam used in the test was of the best average quality which was practical. It was possible to deliver foam to the fire at an average rate of about 30 grams per second (± 15 grams per second) with this equipment. Table XXII presents the quantitative results achieved with this type of liquid foam.

TABLE XXII
LIQUID FOAM EXTINGUISHANT PERFORMANCE AGAINST JP-4 AND EMULSIFIED FUELS

Fuel Type	JP-4	MBF	EF4-104	WSX-7165
Application rate (gr./sec.)	20	27	34	30
Time to extinguish (sec.)	24	16	17	12
Total agent applied (gr.)	487	439	583	330
Equivalent agent per unit of fire surface (lb./ft.^{2})	1.9	1.7	2.3	1.3

It was possible to extinguish all of these fuel fires by covering the fuel with a blanket of foam. The differences between the quantitative results with the four fuels are within the accuracy of the tests and reflect differences in average foam generation rates or the efficiency of foam placement rather than differences in fuel fire response to the foam extinguishant. It is probable that substantially greater effectiveness, on a weight basis, can be shown by mechanical foams where much higher expansion ratios are practical. These data show that liquid foams are effective against both liquid and emulsified fuel fires.

F. SAND AS AN EXTINGUISHANT

Several methods of dispensing sand onto the test fire were evaluated in an effort to control the application rate. It was determined that a careful operator can dispense the sand from a simple scoop in a remarkably uniform manner, and this technique was used for the tests which are reported here. Figures 63 and 64 show the application of sand to the fire in this way. It was possible to apply the sand at an average rate of 48 grams per second (± 5 grams per second). This rate gave good definition to the differences in the fire response to the extinguishant. Table XXIII summarizes the results of the extinguishing tests performed with sand.

TABLE XXIII
PERFORMANCE OF SAND AS AN EXTINGUISHANT AGAINST JP-4 AND EMULSIFIED FUELS

Fuel Type	JP-4	MEF	EF4-104	WSX-7165
Application rate (gr./sec.)	48	43	48	49
Time to extinguish (sec.)	89	38	40	14
Total agent applied (gr.)	4340	1640	1900	700
Equivalent agent per unit of fire surface ($lb./ft.^2$)	17	6.5	7.5	2.8

Sand extinguishes a fire by forming a physical barrier between the fuel and the air. The emulsified fuels generally support the sand, and only enough to cover the fire surface is required as shown in Figure 65. With liquid JP-4, the sand sinks to the bottom of the fuel as soon as it is applied, and enough sand must be used to absorb all of the fuel before it is possible to create the barrier between fuel and air. The amount of sand required to extinguish a burning pool of liquid is thus heavily dependent upon the depth of the liquid. This is not the case with the emulsified fuels, and thus the quantity of 6 to 7 pounds

Figure 63. Standard Fuel Fire Just Prior to Extinguishment With Sand.

Figure 64. Application of Sand to the Standard Fuel Fire.

Figure 65. Sand Supported by Emulsified Fuel in the Burn Pan.

per square foot required to extinguish MEF and EF4-104 may be expected to hold for most emulsified fuel fires. The lower quantity, 3 pounds per square foot, for WSX-7165 may be attributed to the fact that very little liquification of this fuel takes place in the fire and thus there is less liquid to absorb with the sand. The fuel emulsions have a very substantial advantage if fires are to be extinguished with sand.

G. LIQUID WATER EXTINGUISHANT

The liquid water was applied to the test fire as a high-velocity stream as shown in Figures 66 and 67. This simulated the type of flow which might be delivered by a high-pressure hose against a much larger fire. The water was applied at an average rate of 20 grams per second (± 3 grams per second). Table XXIV presents the results of the extinguishing tests performed with water. The stream of water

TABLE XXIV
LIQUID WATER EXTINGUISHANT PERFORMANCE AGAINST JP-4 AND EMULSIFIED FUELS

Fuel Type	JP-4	MEF	EF4-104	WSX-7165
Application rate (gr./sec.)	18	22	18	17
Time to extinguish (sec.)	could not extinguish	43	86	14
Total agent applied (gr.)	could not extinguish	920	1540	240
Equivalent agent per unit of fire surface (lb./ft.^{2})	could not extinguish	3.7	6.1	1.0

was totally ineffective against liquid JP-4 under these test conditions. The application was continued for a 2-minute period and the fire was undiminished at the end of this time. The water tends to spread the fire both by the force of the spray and through the floating action of the

Figure 66. Standard Fuel Fire Just Prior to Extinguishment With a Stream of Water.

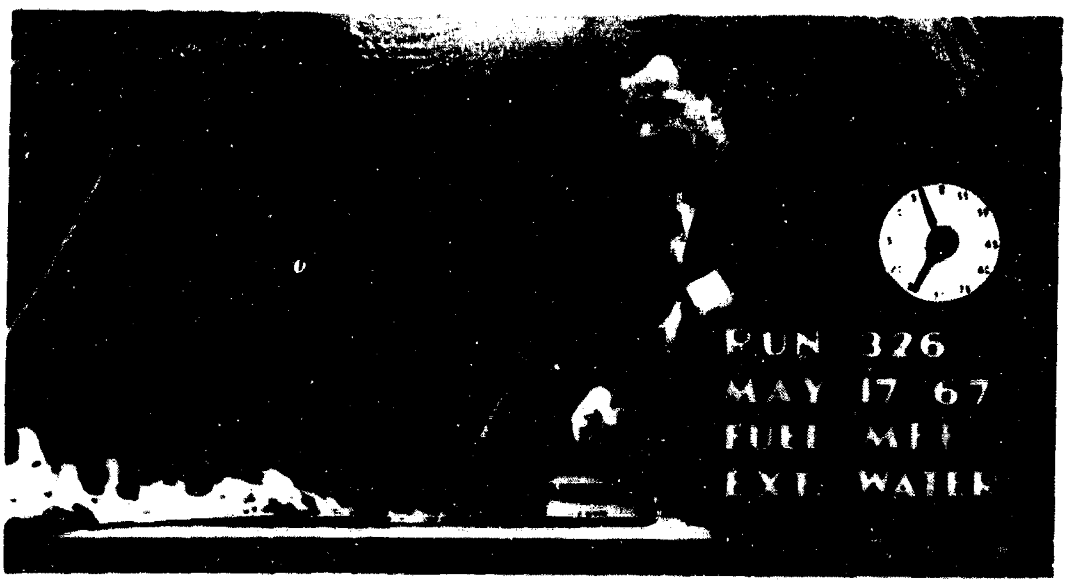


Figure 67. Application of Water to the Standard Fuel Fire.

fuel on the water pool which develops below the fuel. The best that can be accomplished with a stream of water into a liquid JP-4 fire is some temporary cooling of hot metal components. In general, the size, intensity, and violence of the JP-4 fire are increased by a water stream rather than decreased.

Eventually, it was possible to extinguish the MEF emulsified fuel fires with the water stream. The WSX-7165 fire was extinguished quite easily. The emulsified fuels were observed to mix readily with the applied water to produce a milky white fluid. The emulsion appeared to be broken, to some extent, by the applied water. This process released small quantities of liquid fuel which rose to the surface and burned readily while floating. In order to extinguish the fire, it was necessary to cool this floating fuel and to extinguish the flame by persistent application of water to the isolated fire areas. A substantial difference in the response of the three types of emulsified fuel fires was repeated with consistent results and cannot be attributed to experimental variation. This result may be somewhat surprising, since it appears to be at variance with the results obtained with water fog. While the MEF emulsion was more easily extinguished with a stream of water, the EF4-104 was more readily extinguished with the water fog. The WSX-7165 was the most easily extinguished of the three emulsions with both fog and water. This behavior must be related to the way in which the emulsions accept added water and the extent to which they are broken by the heat of the fire and the applied water.

These results would indicate that some consideration of emulsion behavior when exposed to water would be of value. It may be possible to enhance the water extinguishing properties of these fuels to a considerable extent. Even though it was possible to achieve extinguishment of these well-defined fuel fires, the potential hazards associated with scattering the burning fuel with a high-velocity water stream prevent water from being considered as a practical extinguishant at the present time. Nevertheless, because of the obvious economic and logistic advantages inherent in the universal availability of water, its use as an emulsified fuel fire extinguishant should not be lightly discounted. Rather, efforts should be directed toward the development of practical and efficient delivery systems which will permit the application of water to fires under other than the high-velocity stream conditions associated with currently utilized procedures.

H. AIR AS AN EXTINGUISHANT

It is possible to extinguish a fire by causing a burning mixture to move more rapidly than the flame can propagate. For premixed fuel-air mixtures, there exists a characteristic propagation velocity which is dependent only upon the composition of the mixture and the ambient combustion conditions of pressure, temperature, etc. Combustion is maintained by the transfer of heat from the reaction zone, or flame, back to the unburned fuel mixture. Thus, a new increment is raised to the reaction temperature, releases heat, and in turn heats a new increment of unburned material. As the velocity of the stream is increased, the distance over which heat must be transferred increases and the time available decreases. Ultimately, the heat transfer process fails and the flame goes out.

Where there is a pool of liquid present and vaporization of fuel taking place, where the mixing of fuel and air is not ideal, where hot surfaces can contribute to the heat transfer process, and where physical obstructions can produce turbulence in the combustion region, the total process becomes very complex and cannot be analyzed in a simple manner.

The air extinguishing tests which have been performed in this program have employed a high-velocity airstream which could be directed at the fire. This airstream facilitated the establishment of an air barrier between burning fuel and nonburning fuel. Air at an approximate velocity of 40 feet per second from a spray nozzle was found to be a convenient technique for accomplishing this. Figures 68 and 69 show the application methods for air extinguishment and the appearance of the standard fire at the start of run number 313 and at a later time during the extinguishing process. The clock shows elapsed time in seconds.

Table XXV summarizes the results of the extinguishing tests which were accomplished with air. These data are the result of at least three runs in each instance. While it is shown that the test fires could be extinguished with this airstream, it does not appear to be likely that air is a feasible method of extinguishing fuel fires in the aircraft crash environment. This is true for the following reasons. First,

Figure 68. Standard Fuel Fire Just Prior to Extinguishment With an Airstream.

Figure 69. The Application of a High-Velocity Airstream to a Standard Fuel Fire.

TABLE XXV
PERFORMANCE OF HIGH VELOCITY AIR AS AN EXTINGUISHING MECHANISM FOR JP-4 AND EMULSIFIED FUEL FIRES

Fuel Type	JP-4	MEF	EF4-104	WSX-7165
Application rate (gr./sec.)	55	55	55	55
Mass Flow Rate (gr./sec.)	300	300	300	300
Time to extinguish (sec.)	18	7	9	8
Total agent applied (gr.)	5400	2000	2700	2400
Equivalent agent per unit of fire surface (lb./ft.^{2})	21	8	11	10

it is necessary to have an airflow which is broad enough to sweep the entire fire at a single pass. The 4-inch-wide test pan made this relatively easy in the tests conducted. Second, the presence of obstructions in the fire region would act as turbulence generators or flame holders, which could greatly increase airflow requirements. Finally, a high-velocity airstream must be expected to move substantial quantities of fuel which it comes in contact with. Thus, unless the fuel is well confined, as in the test pan, the air would tend to spread the fire.

These test results clearly show that the emulsified fuel fires are easier to extinguish with an airstream than are liquid JP-4 fires. The difference in the time to extinguish the MEF, EF4-104, and WSX-7165 emulsions is within the experimental accuracy of the tests and is not a valid basis for concluding that MEF fires are more easily extinguished than EF4-104 or WSX-7165 fires.

I. SUMMARY OF FIRE EXTINGUISHING RESULTS

Four of the seven extinguishants tested were found to be more effective in extinguishing emulsified fuel fires than

liquid JP-4 fires. These agents were water fog, water, sand, and air. In the case of the other three extinguishing agents, dry chemical, CO_2, and liquid foam, all four types of fuel fires were extinguished with similar quantities of the specific agent being tested. Thus, the use of emulsified fuels would improve the effectiveness of fire-fighting efforts with some extinguishants and would never increase the difficulty of extinguishment with any of the agents tested.

It is important to note also that these tests were performed with equal surface area fires. Fire size will be an important factor in the effectiveness of fire extinguishing efforts. In most crashes of aircraft where fuel containers are damaged, the fuel spills from them to feed the fire.

It is clear that the emulsified fuels have at least an order of magnitude advantage in the size of the fuel pool and fire resulting from leaking tanks or lines which have not suffered massive damage. This type of fuel leakage often occurs in survivable crashes, and thus the use of emulsified fuels could improve the probability of crash fire extinguishment to a much greater degree than the quantitative results from the equal-area fire tests indicate. It is apparent that emulsified fuels present clear and important advantages in aircraft crash fire extinguishment.

VII. FUEL LEAKAGE AND PANEL SELF-SEALING EVALUATION

One of the program objectives was to determine the effect of the emulsified fuels upon the self-sealing action of conventional rubber tank materials and upon the action of coagulant type self-sealing materials. A related objective was to obtain an indication of fuel leakage reduction due to the use of emulsified fuels when complete self-sealing action is not achieved.

Four types of tank panel material were used in these tests. These included caliber .30 and caliber .50 rated conventional self-sealing construction, a crash-resistant urethane-bonded nylon fabric with no sealing layer, and a new type of self-sealing panel which was similar to the crash-resistant panel but had an added layer of liquid coagulant on the inner surface. This panel is still under development.

These panels were subjected to a variety of types of ballistic damage with each fuel. The types of hits included normal or straight-in perforations by caliber .30, caliber .50, and 20 mm ball projectiles; tumbled entrance and exit damage with caliber .30 and caliber .50 ball rounds; and functional API impacts with caliber .30 and caliber .50 projectile sizes. The results of these tests will be reported separately for each type of panel.

A. CALIBER .30 RATED CONVENTIONAL SELF-SEALING PANEL

For these tests, flat panels 18 by 24 inches were clamped between flanges as previously described. The point of bullet perforation was always below the liquid level of the fuel, and generally the fuel head was between 4 and 8 inches at the wound. No backing board or panel support was used either inside or outside the tank. This panel (0.7 lb./ft.^{2}) was tested only against caliber .30 perforations.

This panel material sealed very well against the normal or straight-in hits with caliber .30 rounds. A nearly instantaneous dry seal was achieved with all four types of fuel.

The wound was very small and just barely visible on the outer tank surface for this type of hit. The inner surface showed minute rips (not longer than about 1/8 inch) in the rubber layer, but mechanical closure of the wound was nearly 100 percent and thus sealing could be very effective.

Tumbled perforations through this panel produced some seals and some failures. Liquid JP-4 will continue to flow through the 1/2 to 1-1/2 inch rips produced in this panel by tumbled hits unless the alignment of the damaged sealing layer is good enough to effect a seal. The emulsified fuels did not continue to flow through this type of panel damage, even when a satisfactory seal was not achieved by the panel.

The panel damage which resulted from impacts by functioned caliber .30 API rounds was nearly always so great that a complete sealing of the wound was out of the question. The liquid JP-4 must always be expected to leak from the tank following a hit by a well-functioned incendiary round. The emulsified fuels often did not leak from these wounds; when a flow persisted, it was at a very slow rate, which might best be described as a slight ooze.

An examination of the damaged panels indicated that all three types of emulsified fuels produced the desired swelling action in the sealant layer of the panel, and thus emulsified fuels can be used with conventional self-sealing panels. The reduced flow for emulsified fuels through the larger tank wounds is a significant advantage. The extent of the fuel loss for any particular wound is a function of the internal tank pressure or liquid head and the shear strength of the emulsion. The higher the shear strength of the emulsion, the higher the fuel head that can be resisted before fuel flow will begin and the lower the flow rate after flow has started.

B. CALIBER .50 RATED CONVENTIONAL SELF-SEALING PANEL

The panels tested were flat panels 18 by 24 inches and the material weighed 1.1 pounds per square foot. These panels were clamped between flanges as previously described. All hits were below the liquid level and had a static head of 4 to 8

inches, just as the caliber .30 tests had. These panels were tested with all four fuels in combination with caliber .50 and 20 mm straight-in perforations by ball rounds, tumbled caliber .50 ball hits, and functioned caliber .50 API projectiles. No backing board or other internal or external support was used with any of these tests.

This conventional self-sealing panel performed very well when perforated by straight-in hits with caliber .50 and 20 mm bullets. A very nearly instantaneous dry seal was achieved with each fuel. The mechanical closure of the wound was nearly complete, and thus only a very small amount of sealing through the action of the fuel on the gum rubber layer was needed. All fuels were able to produce the desired swelling of the sealing layer in the panel.

Tumbled caliber .50 ball rounds produced some seals and some failures. Failures to produce a seal, when they occurred, were due to misalignment of the edges of the wound or to "coring out" of the sealing layer. The liquid JP-4 continued to flow through this type of tank wound when good seals were not achieved, but the fuel emulsions generally did not. All three of these emulsions had sufficient shear strength to resist continued flow through a slit of this size under the test conditions.

The damage caused by functioned caliber .50 incendiary rounds passing through these panels was always great enough to prevent satisfactory seals in the tests conducted. The damage produced by the cutting action of the bullet jacket combined with the hydraulic pressure surge and the fire can cause holes and/or rips in the tank wall which are several inches across. Figure 70 shows a functioned caliber .50 M-8 API bullet jacket and core which were recovered from one of these tests. This jagged metal is spinning at a high rate as it goes through the tank wall and must be expected to cut quite a gash in even fairly heavy panel materials. The cut is often expanded by the hydraulic pressure surge which can rip additional fabric. Figure 71 shows the severe damage produced by one caliber .50 API round. Damage was not this extensive on every test, but occasionally even greater rips were caused. Note that while the panel damage is far beyond the self-sealing capability of the material, leakage of the WSX-7165 fuel in the tank is not continuing.

Figure 70. Caliber .50 M-8 API Bullet Core and Jacket Recovered From the Test Tank.

Figure 71. Damage to a Self-Sealing Panel Produced by a Well-Functioned Caliber .50 M-8 API Round (WSX-7165 Fuel).

A fire was started on this test but was extinguished with CO_2 prior to this picture.

C. CRASH-RESISTANT PANELS

The crash-resistant panels tested were made of urethane-bonded nylon fabric material. The material contains no sealing layer at all and thus it is not a self-sealing tank material. Panels 18 by 24 inches were used and were tested in the same manner as the conventional self-sealing panels previously discussed. The material weighed 0.4 pound per square foot. These panels were tested by normal perforations with caliber .30 and caliber .50 ball projectiles and by functioned caliber .30 and caliber .50 API hits in combination with each of the four fuels.

Since these panels contained no sealing layer, all hits against liquid-filled tanks produced continued leakage, and no seals were ever achieved in the strict sense. Normal, straight-in hits by caliber .30 and caliber .50 ball rounds produced very small wounds in the panel, and thus no continued leakage resulted when the emulsified fuels were used.

The damage produced by functioned incendiary rounds was great enough to produce some continued leakage with all fuels. With liquid JP-4, the fuel loss rates were very high. When emulsified fuels were used, the leakage rates varied from very high to very low. Generally, the stiffer WSX-7165 emulsion was more effectively retained, as would be expected, but some slight leakage did continue even with this fuel.

D. COAGULANT TYPE SELF-SEALING PANELS

The central portion of these panels weighed 0.9 pound per square foot without the liquid coagulant. This type of panel construction is under continuing development and differs substantially from other types of self-sealing materials. The unique feature of this approach is a liquid coagulant layer on the inner surface of the panel. The coagulant polymer is carried in a solvent which permits the continued flow of coagulant toward a wound. While the polymer is soluble in the chosen solvent, it is insoluble in JP-4; thus, when the

coagulant solution becomes mixed with fuel, the polymer is released from solution and can proceed to form a tough plug in the tank wound. Ideally, only enough of the coagulant solution would flow to the wound to produce the needed coagulant plug, and the remainder would be available to seal subsequent tank perforations.

The panels which were tested were round so that they could be clamped to the test tank. The central portion of each panel was about 14 inches in diameter and contained the coagulant layer. Around this region was a ring of the fabric and binder buildup without any liquid layer. This could be punched for bolt holes without releasing any of the liquid. Two filler ports were provided on each panel.

The coagulant solution was added to the panel just after its installation on the test tank and before the fuel was placed against it. The coagulant flowed in the bottom filler hole, up through the panel, and out through the top hole so that the panel was completely filled and bubbles eliminated. A reservoir of about 150 ml. of coagulant solution was connected to the lower filler port because of the limited liquid volume of the 14-inch circle of the test panels. This simulated the coagulant solution which would be available from other portions of a complete tank made of this type of construction.

Three types of coagulant solution were provided for test. These were designated as "B", "C", and "D", but details of their composition are not available at this time. Some tests were completed with each coagulant type, but most of the tests were performed with the "C" coagulant. There was no indication that the "B" and "D" coagulants formed better seals than the "C" coagulant used.

These panels were tested in combination with each of the four fuels and were subjected to normal hits by ball rounds of caliber .30, caliber .50, and 20 mm sizes; tumbled entrance and exit perforations by caliber .50 ball rounds; and functioned caliber .30 and caliber .50 API damage. The metal test tank shown in Figure 31 was used for all normal caliber .30 and caliber .50 tests with both ball and API rounds. The tumbled caliber .50 rounds and the 20 mm rounds were fired into 2-foot cubical tanks made of a conventional self-sealing material. A 14-inch circle of the tank material

was removed, and the self-sealing panel was clamped between steel flanges in its place. The sides and bottom of the cube tanks were lightly supported with 1/4-inch plywood, but the test panel was not supported in any way.

The panels sealed well against normal, straight-in perforations by caliber .30, caliber .50, and 20 mm rounds. It appeared that suitable coagulant plugs formed with this limited damage. Some question might be raised relative to the seals with 20 mm perforations, since the cube tanks failed on the exit side and thus fuel did not stand against the test panel for very long after the impact. Mechanical damage to the panels was quite limited, and the coagulant seals appeared to be adequate to prevent fuel leakage with liquid JP-4. The emulsified fuels would not have flowed freely through this type of perforation even if the coagulant plug were not adequate.

Dry seals were generally achieved almost instantaneously with the caliber .30 and caliber .50 perforations. An examination of the panels after the tests indicated that most of the liquid coagulant usually drained from the panel on the inside of the tank. This produced a considerable coagulant mass in the bottom of the tank.

The tumbled caliber .50 entrance and exit tests were performed using the 2-foot flexible cubes. Two sheets of 0.090-inch aluminum set at 38 degrees to the line of fire were used to induce tumbling of the projectile.

Five tumbled entrance hits produced two apparent coagulant seals and one of these was with liquid JP-4. A second liquid JP-4 test failed to produce a coagulant seal. Four exit perforations produced two possible coagulant seals, but neither of these was with the liquid JP-4. Some question relative to the quality of the coagulant seals achieved always existed with the emulsified fuels, since they usually did not continue to flow from the tank even if the seal was not achieved with the coagulant.

Figures 72 and 73 show the best coagulant plug formed in this series of tests with liquid JP-4. Figure 72 shows the exterior surface of the panel; Figure 73, the interior surface. Note that much of the coagulant polymer ran down the inside surface and was not effective.

Figure 72. Plug Formed on the Exterior of a Coagulant Type Self-Sealing Panel by the Action of a Tumbled Caliber .50 Bullet and Liquid JP-4 Fuel.

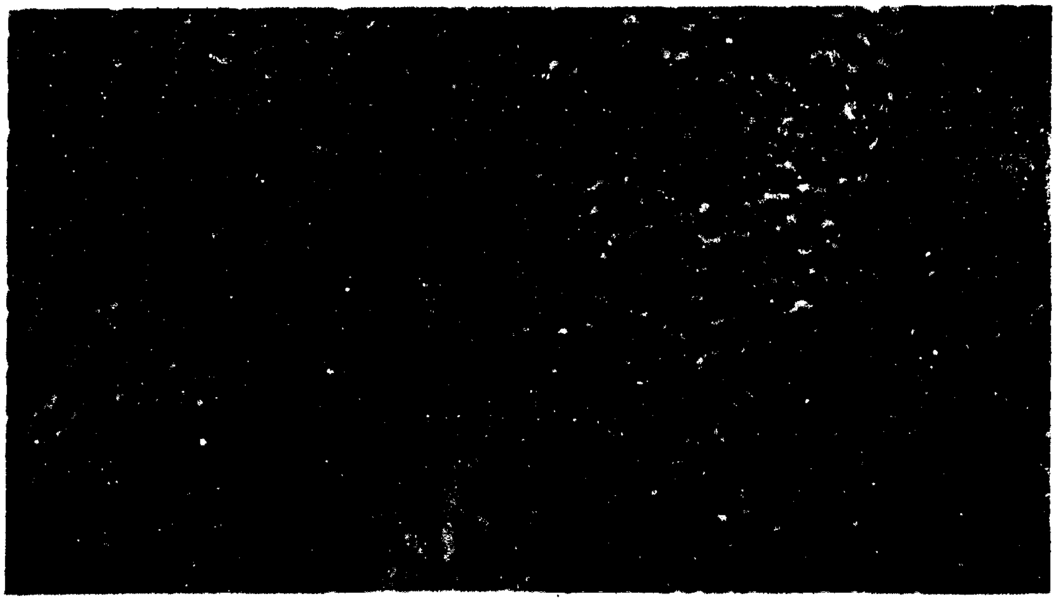


Figure 73. Plug and Leakage on the Interior of a Coagulant Type Self-Sealing Panel by the Action of a Tumbled Caliber .50 Bullet and Liquid JP-4 Fuel (Same Test as Figure 72).

VIII. CONCLUSIONS

The understanding of the behavior of liquid and emulsified JP-4 in the aircraft environment which has been gained through the study and testing conducted on this program provides a basis for a number of significant conclusions. It is believed that the data developed in this study are adequate to support the conclusions, regarding fuel vulnerability and related factors, which follow.

1. The WSX-7165 emulsion burns, or is consumed, at a somewhat lower rate than liquid JP-4, MEF, or EF4-104 emulsions under constant fire surface area conditions. This difference is greatest at the highest air rates and is believed to be related to the stability of this emulsion in the fire.

2. The burning rates of all the fuels tested are similar at air rates below 15 feet per second.

3. Fuel-burning rates increase in proportion to increases in airflow for liquid JP-4, MEF, and EF4-104 emulsions. The fuel-burning rate for WSX-7165 increases with increasing airflow rate up to 15 or 20 feet per second, but it appears to be reaching a limiting value at about 25 feet per second.

4. Fuel-burning rates are independent of air temperature within the limits of 40°F to 110°F and may be essentially independent of temperature over a much wider range.

5. MEF and EF4-104 emulsions require nearly 10 times as long as liquid JP-4 to form explosive fuel-air mixtures above an open fuel surface such as that in the test chamber. The WSX-7165 emulsion requires 100 times as long as liquid JP-4 to reach the lean explosive limit.

6. The slow vaporization rates which have been demonstrated for emulsified fuels make tank vapor space protection, through the use of a ventilating airstream, practical for these fuels. This type of passive defense is not practical with liquid JP-4.

7. All fuels tested permeate a 4-mil polyethylene bladder at similar rates.

8. The venting of tank vapor spaces with air would provide satisfactory vapor space explosion protection for liquid JP-4 or any of these emulsions contained within a 4-mil polyethylene bladder.

9. The emulsified fuels tend to cohere longer and to form larger fuel droplets or chunks than liquid JP-4 following ballistic impacts or fuel drops onto a hard surface.

10. The geometry of fuel spray patterns formed by the emulsified fuels differs but little from liquid JP-4 sprays expelled from the BRL fuel nozzle or ballistic wounds in fuel tanks. The differences which were found generally favor the fuel emulsions from a vulnerability standpoint.

11. The radius of probable fuel ignition is much smaller for the three fuel emulsions than for liquid JP-4 under the conditions of the fuel drop tests in this program. This is true for both electric spark and hot metal ignition sources. The hot metal surface proved to be a much stronger ignition source than the electric spark.

12. Friction spark ignition of fuel droplets moving through the air is difficult to accomplish. While such ignitions are clearly possible, they are not probable for any of the fuels tested.

13. Friction spark ignition of a freely vaporizing layer of fuel on a stationary surface is probable and can be accomplished with relative ease for liquid JP-4 and all three emulsions. The spark stream must be aimed at the fuel surface and be continued for up to several seconds to make such ignitions very probable.

14. The ignition of fuel sprayed from fuel tanks by ballistic impacts with functioned incendiary ammunition is certain whenever the incendiary burst is produced in the region just outside the fuel tank. Continuing fires were initiated by both caliber .30 and caliber .50 API bullets in combination with liquid JP-4 and each of the fuel emulsions. It is important to note that the fires involving emulsified fuels were generally smaller, less violent, and easier to extinguish than liquid JP-4 fires.

15. Emulsified fuel fires are more easily extinguished than liquid JP-4 fires with the following extinguishants: water fog, sand, water, and air. Of these four, water fog and sand are the most practical for use on emulsified fuel fires.

16. Emulsified fuel fires show no significant differences, when compared with liquid JP-4 fires, in their response to dry chemical, CO_2, or liquid foam extinguishants.

17. The MEF, EF4-104, and WSX-7165 emulsions react well with conventional self-sealing fuel tank materials and may be used with such panels without any reduction in self-sealing action.

18. The emulsified fuels react satisfactorily with the coagulant type sealing panels.

19. The emulsified fuels are often retained in severely damaged tanks which would permit liquid JP-4 to flow freely from the wound.

20. Emulsified fuels offer opportunities for greater aircraft survivability from several standpoints. They may best be employed as a part of a total passive defense system for aircraft fuel. Such a total system will require crash-resistant and self-sealing fuel tanks, internal vapor space protection, and external void protection for spaces around fuel tanks.

IX. RECOMMENDATIONS

The following recommendations are offered as guidance to the future development and application of emulsified fuels and related fuel protection systems.

1. Emulsified fuels for use in aircraft should have the maximum apparent viscosity or shear strength which is consistent with the fuel-handling components that must be used to move the fuel from the tank to the combustion unit.

2. Aircraft fuel tanks which are used to contain emulsified fuels should be equipped with a vent airstream to provide vapor space explosion protection.

3. Voids which are external to emulsion filled fuel tanks but internal to aircraft structure should be filled with foam or other suitable void fillers to prevent or reduce fuel ignitions by incendiary ammunition.

4. The minimum effective thickness of this void filler protection material should be determined for specific fuels and specific filler materials.

5. The shear breakdown of the WSX-7165 emulsion by ballistic impacts is undesirable from a vulnerability standpoint and should be reduced or eliminated.

6. The very great stability of the WSX-7165 emulsion in a fire environment is of help in limiting the size and intensity of fuel fires and can be of direct assistance in extinguishing an aircraft fire. This property should be maintained in emulsified fuels for aircraft use.

7. The explosive vapor tests which have been completed indicate the possibility of some flame-inhibiting effect with vapors formed from the WSX-7165 fuel. This possibility should be investigated and exploited to the extent that this is possible.

8. Emulsified fuels should be contained by crash-resistant and self-sealing tanks to the maximum extent possible. The strength of the fuel mass aids confinement in a damaged tank

but cannot eliminate the need for strong tanks from the passive defense standpoint.

9. Detailed comparisons of the different emulsified fuels should be made using emulsions made from the same JP-4 base stock by manufacturing techniques which are the same or at least closed systems in each case.

APPENDIX I

BASIC DATA ON FUELS USED IN THE TEST PROGRAM

The liquid JP-4 used in this test program was purchased from the Sky Harbor Air Service at the Municipal Airport in Cheyenne, Wyoming. The fuel was produced by the Frontier Refining Company in Cheyenne. The shipping report which follows indicates the source and blend of the fuel, and the Frontier Inspection Report indicates the specific properties of this fuel lot.

THE [illegible] REFINING COMPANY

Cheyenne, Wyoming

Running Gallons 142,653

INSPECTION OFFICE DCRS/[illegible]

Date 3-7-67

Shipped To

PHILLIPS PETROLEUM COMPANY
c/o SKY HARBOR AIR SERVICE
MUNICIPAL AIRPORT
CHEYENNE, WYOMING

9130-256-8613 (JP-4)
SPECIFICATION MIL-T 5624-G

Seal #	B/L #	Truck # - Hose		Net gallons
[illegible] 20628-631	B-6189	2	Sky Harbor	2035

Loaded from Tank # 7 Approved 3-6-67 Gravity Group 3 Blend # 307

CONTAINS FUEL SYSTEMS ICING INHIBITOR
CONTAINS 40/1000 Bbls. SANTOLENE C CORROSION INHIBITOR

The supplies comprising this shipment have been subjected to and have passed all examinations and tests required by the contract, were shipped in accordance with authorized shipping instruction, and conform to the quality, identity, and condition called for in contractual requirements and to the quantity shown on this document. This shipment was released in accordance with the Armed Services Procurement Regulation for Authorizing Shipment of Supplies under authority of RAY TOUPS, QAR in a letter dated July 14, 1966.

[illegible signature]
Traffic Manager

Ray Toups
RAY TOUPS, QAR

THE FRONTIER REFINING COMPANY
Cheyenne, Wyoming

DATE 6 March 1967

Specification & Grade No. MIL-T-5624G, Amended and Contract Provisions (JP-4)
Company Blend No. [illegible] Tank No. [illegible] Barrels [illegible] Net Gallons [illegible]
Contract No. [illegible]
Contractor THE FRONTIER REFINING COMPANY, Denver, Colorado

	THE FRONTIER REFINING COMPANY Inspection Results	SPECIFICATION MIL-T-5624G, Amended, and Contract Provisions
Gravity, ° API @ 60°F.	[illegible]	45-57
Specific Gravity @ 60°F.	[illegible]	-
Sulfur, % by Weight	[illegible]	0.40 Max.
Reid Vapor Pressure, lbs.	[illegible]	2.0-3.0
Aromatics, %	[illegible]	25.0 Max.
Olefins, %	[illegible]	5.0 Max.
Freezing Point, °F.	[illegible]	-72°F. Max.
Water Reaction	1	1 b Max.
Particulate Matter, Mg/Gal.	[illegible]	4.0 Max.
Corrosion (Copper Strip)	1	No. 1 Max.
Smoke Point Volatility Index	[illegible]	Not less than 52.0
Smoke Point, mm	[illegible]	
GUM:		
Steam Jet, 400°F., mgm/100ml	0.8	7 mg Max.
Accelerated (16 hrs O_2 bomb mgm/100 ml)	[illegible]	14 mg Max.
HEAT OF COMBUSTION:		
B.T.U. /lb.-Net.		18,400 BTU/lb Min.
Aniline-Gravity Product	[illegible]	5,250 Min.
Aniline Point, °F.	[illegible]	
Color, Saybolt, D-156	[illegible]	
Doctor Test	[illegible]	
Mercaptan Sulfur, %	[illegible]	0.001 Max.
DISTILLATION: (% Evap. @ 760 mm Hg.)		
I.B.P., °F.	[illegible]	To be reported
5%	[illegible]	
10%	[illegible]	To be reported
20%	[illegible]	290°F. Min.
30%	[illegible]	
40%	[illegible]	
50%	[illegible]	370°F. Max.
60%	[illegible]	
70%	[illegible]	
80%	[illegible]	
90%	[illegible]	470°F. Max.
95%	[illegible]	
End Point, °F.	[illegible]	To be reported
% Recovery	[illegible]	
% Residue	[illegible]	1.5 Max.
% Loss	[illegible]	1.5 Max.
% Evap. @ 400°F.	[illegible]	To be reported
Water Separometer Index	[illegible]	70 Min.
THERMAL STABILITY:		
Change in pressure drop in 5 hrs. In.Hg.	0.0	3 In. Max.
Preheater Deposit	1	Less than 3
% Anti-Icing Agent: UPPER [illegible] MIDDLE [illegible] LOWER [illegible]		0.10-0.15% Max.

NOTE:
1. 4 #/1000 Bbl. Santolene "C" Corrosion Inhibitor Added.
2. (a) ________ Gallon sample on this blend submitted to Wright Patterson A.F. Base.
(b) W.P.A.F.B. Sample No. ________
(c) Sample drawn by [illegible]
3. This fuel conforms to Specification MIL-T-5624G, Amended, and Contract Provisions for JP-4 and consists completely of hydrocarbon compounds, except as noted on above certificate and this fuel is suitable for use. ALL tests were performed by the methods prescribed in the applicable specifications.

BAROMETER [illegible]
ALTITUDE [illegible]

[illegible]
Chief Chemist

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The MEF fuel emulsion used in the test program was received from two sources. The initial shipment was manufactured by the Monsanto Research Corporation, Dayton, Ohio. This fuel was used for the burning rate, explosive vapor rate, fire extinguishing, fuel drop dispersion, and ignition tests; fuel spray dispersion and ignition tests; and for some of the ballistic dispersion and ignition tests. The JP-4 used to make this fuel was secured from Ashland Oil and Refining Company, Findlay, Ohio. The fuel inspection data on this JP-4 are shown on the report form which follows.

An additional shipment of MEF emulsion was received late in the test program. This fuel was prepared by the U. S. Army Fuels and Lubricants Research Laboratory in San Antonio, Texas. This fuel was used for some of the ballistic dispersion and ballistic ignition tests. The only data available relative to this fuel are included in the letter which follows.

Tested: Findlay Ohio
Ashland Oil & Refining Company

Date 1 - 5 66

Contract No. DSA - 600 - 11562

Tank No. 182

Specification Mil - T - 5624 G

Sample Origin Findlay, Ohio

Product & Grade JP-4

Quantity 357,992 gallons

	Tank	Barge	Spec.
Sample No.	Batch - 29		
Gravity, °API	53.2		45-57
RVP (#)	2.95		2-3
Distillation			
Initial	136		Record
10%	188		Record
20%	206		Record
50%	288		Record
90%	384		Record
E. P.	468		Record
Residue	[illegible]		1.5% max.
Loss	.5		1.5% max.
% evap. @ 290° F.	51		20 min.
370° F.	85		50 min.
400° F.	93		Record
470° F.			90 min.

	Tank	Spec.
Color	Clear	Record
Corrosion, Air Wall	1A	1 max.
Freeze Point, °C	-66	-76 max.
Exist. Gum mg/100 ml	.8	7 max.
Pot. Gum mg/100 ml	2.6	14 max.
Total Sulfur, %	.118	0.4 max.
Water Tolerance	0.0⁄1	1 max
Olefins, %	.72	5.0 max.
Aromatics, %	7.76	25 max.
Mercaptan, %	.0005	.001 max.
Doctor Test	Sweet	Record
Aniline Point	137	Record
Aniline Gr. Constant	7623	5250 min.
Smoke Point, MM	31.6	Record
Smoke Vol. Factor	90.7	52.0 min.
Rust Content		mg per gal.

Metal Deactivator: N,N'-disalicylidene-1, 2-propane-diamine . . . . 2 # per 1000 barrels

Corrosion Inhibitor: Santolene C . . . . 4 # per 1000 barrels

Anti-Oxidant: N,N'-Disecondary butyl paraphenylenediamine . . . . ____ # per 1000 barrels

Thermal Stability @ 6#/Hr. for 5 Hrs. Spec. Anti-Icing

" Hg Δ P @ 300°/400° 0.1 (3)" Max. Top .11

Max. Preheater tube deposit 1 Less than 3 Middle .11

Modified Water Separometer Index 100 Bot .11

Seal Numbers 56173 - 56176 inclusive

The results herein are certified to be correct and true

J. F. Brimmer

Technical data relative to the JP-4 used by Monsanto Research Corp. to produce the fuel emulsion shipped January 25, 1967, to Falcon R&D.

SOUTHWEST RESEARCH INSTITUTE

8500 CULEBRA ROAD SAN ANTONIO, TEXAS 78206

June 7, 1967

Mr. George Custard
Falcon Research & Development Co.
Technodyne Division
1441 Ogden Street
Denver, Colorado 80218

Dear Mr. Custard:

We are shipping, via motor freight, four (4) 55-gallon drums of emulsified JP-4 as discussed with Mr. Bill Nolan of AVLABS for Contract DA-44-177-AMC-415(T). Each drum of emulsified fuel was prepared separately, and yield values range from 1000 to 1200 dynes/cm^2 at the time of shipping.

Very truly yours,

R. D. Quillian, Jr., Director
U. S. Army Fuels & Lubricants
Research Laboratory

John N. Bowden

John N. Bowden
Senior Research Chemist

JNB:ga

cc: Dr. C. F. Pickett, AMKCC
Mr. Wm. J. Nolan

The EF4-104 fuel used in the program was supplied by the Air Logistics Corporation of Pasadena, California. The JP-4 used to make this emulsion was secured from the Atlantic Richfield Company, Watson Refinery. The laboratory certificate for this fuel follows.

AtlanticRichfieldCompany

WATSON REFINERY

LABORATORY CERTIFICATE

SAMPLE OF TURBINE FUEL, AVIATION, GRADE JP-4
Specification: MIL-T-5624G, Amend. 1

FILE NO. 581.1

DATE May 24, 1967

FROM Tank 165 - 4 Drums - Shipped 5/24/67

DATE TESTED

INSTRUCTIONS OF Air Logistics Corporation
3600 East Foothill Boulevard
Pasadena, California

REFERENCE NO. Req. #P-1927

TESTS	SPEC.	
Gravity, °API	45-57	55.5
Color, Saybolt	-	-7
Distillation - IBP, °F	-	152
10% Evap., °F	-	196
20% Evap., °F	290 max.	215
50% Evap., °F	370 max.	263
90% Evap., °F	470 max.	387
End Point, °F	-	468
Residue, %	1.5 max.	1.0
Loss, %	1.5 max.	1.0
% Evap. @ 400 °F	-	92
Existent Gum, mg/100 ml	7.0 max.	0.8
Potential Gum, mg/100 ml	14.0 max.	2.0
Sulfur, total, % by wt	0.4 max.	0.06
Mercaptan Sulfur, % by wt	0.001 max.	0.0003
Reid Vapor Pressure, psi	2.0-3.0	2.4
Freezing Point, °F	-72 max.	Below -80
Aniline Gravity Product	5,250 min.	7,132
Aromatics, % by vol	25.0 max.	9.0
Olefins, % by vol	5.0 max.	0.5
Smoke Volatility Index	52.0 min.	69.6
Corrosion, Cu Strip, ASTM	No. 1 max.	No. 1a
Water Reaction	1b max.	1b
Water Separometer Index Modified	70 min.	90
Thermal Stability: Pressure Drop, psi	3.0 max.	0.0
Preheater Deposit	<3	0
ADDITIVES, #/M bbls:		
Corrosion Inhibitor	4.0-16.	4.25
Antioxidant	8.4 max.	4.0
Metal Deactivator	2.0 max.	0.50
Icing Inhibitor, % by vol	0.10-0.15	0.116
Particulate Contaminant, mg/gal. FOB origin	4.0 max.	1.14

GWB/sc

cc: Mr. D. R. Dieudonne

BY P. T. Brown

WL. NO.

The WSX-7165 emulsified fuel was supplied by the Enjay Chemical Company of Houston, Texas. The fuel batch number and the laboratory report data for the JP-4 used to produce this fuel are included in the documents supplied with the fuel which follow.

ENJAY

ENJAY CHEMICAL COMPANY

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Chemical Specialties Division

Oil Field Chemicals
M. R. Morrow, Marketing Manager

August 11, 1967

Mr. John F. Wear
Falcon Research & Development Company
1441 Ogden Street
Denver, Colorado 80218

Dear Mr. Wear:

The enclosed sheet lists inspection data for the JP-4 used in the emulsified fuel which you received in late July.

Our batch number was 2830, manufactured July 27. If we can be of further service, please contact us.

Sincerely,

J. E. Haughn

JEH:wm
Enclosure

cc: Bill Nolan
Dr. Tom Wallace
EMC

Tank A-25 JP-4

Aniline x Gravity	7504
Aniline point	140
Aromatics	11.5% volume
Saybolt color	+30
Corrosion test	1A
Doctor test	Passes
Freeze point	-88°F
Gravity, API	53.5
Existent gum	0.6 mg/100 cc
Potential gum	7.4 mg/100 cc
Olefins	1.5% volume
Preheater deposit code	1
Pressure drop	0.2
Smoke point	27 mm
Smoke volatility index	59.76
Sulfur	0.005% wt.
Mercaptan sulfur	0.0001% wt.
Reid vapor pressure	2.8
Water tolerance	Passes 0.0 (1)
Initial boiling pt.	144°F
10%	269
20%	278
50%	306
90%	456
Final boiling pt.	500
Recovery	98%
Loss	1%
Residue	1%
% Distilled at 400°F	78
W.S.I.M.	87
Particulate contaminants	0.8 mg/gal
Santolene C	5 lbs/1000 bbls

APPENDIX II

ENGINEERING TEST PLANS FOR THE PERFORMANCE OF PROJECT TASKS

ENGINEERING TEST PLAN NUMBER 3

FUEL COMBUSTION RATE TESTS

The fuel combustion rate tests are to be conducted in the following manner:

1. Weigh 1000 grams of fresh fuel into the combustion container.
2. Place the combustion container in the burn position.
3. Adjust the airflow and air temperature to the planned values.
4. Set the timer to zero.
5. Ignite the fuel and start the clock.
6. Record the time when the first 100 grams of fuel have been consumed.
7. Permit the fire to continue to burn until all fuel has been consumed; record the time at each 100-gram increment.
8. Take a photograph of the fuel fire immediately after ignition and at intervals during the burning process.
9. Take moving picture documentation on selected runs so that the differences in fuel combustion rates can be visually noted.
10. Complete three runs for each fuel and test condition.

Test runs will be performed at air velocities of 5, 15, and 25 feet per second and at air temperatures of 40°, 70°, and 100°F.

Data are to be recorded on the data sheet which is provided.

ENGINEERING TEST PLAN NUMBER 4

EXPLOSIVE VAPOR FORMATION RATE TESTS

The explosive vapor formation rate tests are to be conducted in the following manner:

1. Weigh the required quantity of fresh fuel into the container and level the fuel surface if necessary.

2. Place the fuel and container in test position after determining that there is no residual fuel from earlier tests.

3. Set the timer to zero.

4. Turn on the stirrer and vent the airstream as required.

5. Lower the vapor chamber over the fuel and start the timer. Be sure that all seals are effective.

6. Fire the ignitor at established time intervals.

7. Note the results of each initiation cycle. Note any changes in temperature during the test.

8. Continue the test until an explosion is achieved, if this is possible.

9. Since there is a possibility that some combustion of fuel will take place on ignition tests which do not produce an explosion, steps 1 through 8 are a preliminary screening test. For the final determination of the shortest time to reach an explosive mix, repeat steps 1 through 8. Use as the time of the <u>first</u> ignition the time to reach an explosion in the earlier test less 10 percent.

10. If an explosion is achieved in 9, repeat again with a subsequent time reduction. If no explosion is achieved, continue the ignition cycles as in 8.

11. Repeat the tests until the time to reach an explosive mixture is confirmed by two observations which do not vary by more than about five percent.

12. Tests involving a bladder material will be conducted in the same manner as the open fuel tests except that the fuel will be completely confined in the bladder. Bladder tests will be continued for a 24-hour period unless an explosion is produced sooner.

13. Tests involving vent air will be conducted in the same way with the addition of the measured airstream through the chamber.

14. Data will be recorded as called for on the data sheet provided.

ENGINEERING TEST PLAN NUMBER 5

FUEL EXTINGUISHING CHARACTERISTICS

The tests of fire extinguishing characteristics for JP-4 and the emulsified fuels are to be conducted in the following manner:

1. Set the airflow to approximately 15 feet per second and the air temperature to about 70°F.

2. Weigh the required quantity of fresh fuel into the container and level the fuel surface if necessary.

3. Place the fuel and container in test position after determining that there is no residual fuel from earlier tests.

4. Set the timer to zero.

5. Apply the heat source and ignition source to the fuel until sustained combustion of fuel is achieved. Start the timer when heat is first applied to the fuel.

6. Note on the data sheet the time at which sustained fuel combustion was obtained.

7. Allow the fuel to burn for 3 minutes to establish the "standard fire". Photograph this fire just prior to the start of extinguishment.

8. Weigh the extinguisher. Then apply the extinguishing agent to the "standard fire" at the rate agreed to prior to the start of the test.

9. When fire is extinguished, stop the timer and the application of the extinguishing agent.

10. Weigh the extinguisher again to determine the amount of agent used. For water, fog, air, etc., determine the rate of application and note carefully the time period of application.

11. Secure the following photographic documentation for each test:

    a. Still photo of fire immediately prior to the start of extinguishment.

    b. High-speed 16 mm color photographs of each fuel with each extinguishing agent. Camera speed will be selected for optimum coverage of each test.

CAUTION: The application of some extinguishing agents may be expected to cause fuel to be spilled from the pan. The test personnel must anticipate this and be certain that spilled burning fuel will not cause injury to other personnel in the area or to test facilities.

ENGINEERING TEST PLAN NUMBER 6

FUEL DISPERSION CHARACTERISTICS

The tests of the fuel dispersion characteristics of JP-4 and the emulsified fuels are to be conducted in the following manner.

Three types of tests are to be conducted. The purpose of these tests is to develop comparative data relative to the physical behavior of these fuels through the spray patterns which result from bullet impacts on fuel tanks and the splatter patterns which result when fuel is spilled. Comparative data relative to droplet size and dispersion pattern shape and size are to be secured to the maximum extent practical.

Flat Surface Impact Tests

1. Initial tests are to be performed with JP-4 at a drop height of 20 feet; other tests will be performed from drop heights of 10 feet and 5 feet.

2. Two hundred and fifty grams of fuel are to be contained in a light plastic film. The shape of the fuel mass is to be approximately spherical.

3. The fuel is to be suspended by solenoid action over a suitable flat surface at the 20-foot height. The surface will be of concrete and marked with a grid pattern.

4. High-speed photographic documentation is to be secured for each test. An initial framing rate of 2000 frames per second will be used. The lighting and camera synchronization will be such as to give the best possible view of the fuel impact and the resulting spillage and droplet dispersion.

5. Guide wires are to be used to insure that the fuel mass impacts at a known point on the surface.

6. Fuel quantities and camera framing rates will be adjusted on subsequent shots to insure the best data record.

7. When satisfactory test results have been achieved with JP-4, the identical tests are to be performed using the emulsified fuel so that direct comparisons will be possible.

8. Still pictures of test equipment and test results will be taken for use in a report wherever the results will be helpful to the reader.

   High-speed motion pictures will be taken with black and white film on preliminary runs and for report picture purposes.

   High-speed motion picture color runs will be taken of each fuel drop condition after the optimum conditions for the photographing of the tests have been determined.

9. The following data will be recorded for each drop test.

   a. fuel type
   b. fuel weight
   c. type of fuel confinement
   d. drop height
   e. camera framing rate
   f. camera f stop
   g. lighting conditions
   h. film type
   i. planned time interval between fuel release and camera start
   j. ambient conditions, temperature, wind, etc.
   k. dispersion patterns
   l. comments regarding results
   m. run number
   n. date
   o. name of person responsible for data recorded

<u>Fuel Spray Tests</u>

The fuel spray tests will be conducted with the BRL fuel spray device (an electrically primed caliber .50 cartridge case with holder, timer, etc.). This device has been shown to produce a fuel spray which closely approximates, in

quantity, velocity, and dispersion, the spray resulting from caliber .50 bullet impacts on self-sealing fuel cells.

1. Caliber .50 cartridge cases are to be cleaned inside and outside prior to use. The mouths of the cases are to be checked for smoothness and roundness prior to use.

2. Electric primers are to be carefully pressed into the cases after used primers have been removed.

3. Cases are to be filled to the brim with fuel and covered with a small piece of tissue paper to retain the fuel in the firing position. Care should be taken to insure that no air is entrapped during the filling of the cases.

4. The spray device is to be fired horizontally and the emerging spray photographed to produce the best possible photographic image. Particular emphasis will be placed upon the spray pattern produced in the first 18 inches beyond the mouth of the nozzle; however, the pattern to 3 feet or more will be of some interest. It is probable that fuel sprays produced within aircraft structure will strike some internal component within the first 18 inches of travel; however, there are occasional circumstances where longer spray patterns are possible. A baffle will be placed at 18 inches from the nozzle on some tests.

5. Initial tests to develop lighting techniques and to produce pictures for use in reports will be taken with black and white film. Following these tests, high-speed color motion pictures will be taken of the spray produced by each fuel type.

6. Still pictures of the test equipment will be taken prior to the start of the tests.

7. The following data will be recorded for each test:

   a. fuel type
   b. camera framing rate
   c. camera f stop

d. lighting conditions
e. film type
f. planned time interval between camera start and nozzle firing
g. ambient conditions, temperature, wind, etc.
h. comments regarding results
i. run number
j. date
k. name of person responsible for data recorded

<u>Ballistic Impact Tests</u>

The purpose of these tests is to evaluate the influence of fuel type upon the spray produced by ballistic impacts on several types of fuel cell material which may be used to contain future aircraft fuels. The performance of conventional and newly developed self-sealing materials with emulsified fuels will also be determined as a product of these tests.

The tests are to be conducted in the following manner.

1. Ball ammunition or AP ammunition is to be used for all ballistic impact tests. Incendiary ammunition is to be used in later tests involving ignition, but no incendiary ammunition types are to be used in these tests since the fires would prevent observation of fuel spray patterns. Caliber .30, caliber .50, and 20 mm ammunition will be used.

2. Ammunition will be used at service velocity and a range of approximately 100 feet for all tests.

3. Test fuel cell panels will be clamped to the test tank between flanges.

4. The test tank will be 14 inches inside diameter and 36 inches long and will provide for test panels on the impact and exit surfaces. If tests indicate that a rigid-wall tank imposes too severe a load on the test panels, with 20 mm rounds, elastic test tanks will be used.

5. Test tanks will be filled to approximately 80 percent of capacity with the fuel to be tested.

6. All ballistic impacts are to be below the liquid level and at about 1/2 the fuel depth.

7. High-speed motion picture documentation is to be used with each test. The fuel spray from the front surface is of primary importance; however, at least one test of each type will include high-speed photography of the fuel spray and spillage from the back of the tank.

   Still photographs of fuel leakage and/or test panel condition will be taken <u>before</u> panels are removed from the test tank.

8. The following data items will be recorded for each test.

   a. ammunition caliber and type
   b. fuel cell material used
   c. fuel type
   d. camera framing rate
   e. camera f stop
   f. camera lens used
   g. lighting conditions
   h. film type
   i. planned time interval between camera start and power to firing circuit
   j. ambient conditions, temperature, wind, etc.
   k. comments regarding results
   l. run number
   m. date
   n. name of person responsible for data recorded

ENGINEERING TEST PLAN NUMBER 7

FUEL IGNITION CHARACTERISTICS

The tests of the fuel ignition characteristics of JP-4 and the emulsified fuels are to be conducted in the following manner.

Three types of tests are to be conducted. The purpose of these tests is to develop comparative data relative to the ignition behavior of these fuels for the types of spray patterns which result from bullet impacts on fuel tanks and the splatter patterns which result when fuel is spilled. Comparative data relative to the fuel spray ignition by four types of ignition sources are to be secured to the maximum extent practical. Generally, the flat surface and BRL fuel spray tests will use the electric spark, hot metal surface, and friction sparks; the ballistic impacts will employ incendiary bursts.

Flat Surface Impact Tests

1. Initial tests are to be performed with JP-4 at a drop height of 20 feet.

2. 250 grams of fuel are to be contained in a light plastic film. The shape of the fuel mass is to be approximately spherical.

3. The fuel is to be suspended by solenoid action over a concrete surface which has been marked with a grid.

4. High-speed photographic documentation is to be secured for each fuel type and drop condition at a framing rate of 2000 frames per second. The lighting and camera synchronization will be such as to give the best possible view of the fuel impact and the resulting fuel ignition.

5. Guide wires are to be used to insure that the fuel mass impacts at a known point on the surface.

6. When satisfactory test results have been achieved with JP-4, the identical tests are to be performed using the emulsified fuel so that direct comparisons will be possible.

7. The ignitor variation will be performed in the following way:

   a. First, tests are to be run using JP-4 with the electric spark ignition source. (This will be a continuous AC spark.)

   b. From an analysis of the dispersion test data, determine a distance from the impact point where an ignition is probable. Place the ignitor at this point.

   c. Drop the fuel and observe the results.

   d. If an ignition occurs, move the ignitor out 1 foot and repeat the test.

   e. If no ignition occurs on the first test, complete three tests at this location.

   f. If the three tests produce two ignitions, move the ignitor out an additional foot. If less than two ignitions are produced, complete five tests at this point.

   g. If the five tests show less than 50 percent ignitions, this will be established as the ignition limit for the test condition. If more than 50 percent ignitions are achieved, again move out 1 foot and repeat five tests.

   h. Repeat steps a through g with JP-4 and the hot metal surface ignition source.

   i. Repeat a through g with JP-4 and the friction spark ignition source.

   j. Repeat all tests (a through i) with the MEF emulsion.

   k. Repeat all tests (a through i) with the EF4-104 emulsion.

   l. NOTE: While the electric spark ignition source is essentially a point source, the hot surface and friction spark ignitors will be more nearly line or plane

sources. The line or plane will be oriented in a plane, which is parallel to the line of drop so that the distance from impact point to ignitor is clearly known and not confused by the dimensions of the surface itself.

m. Record all test data which are pertinent on the attached data form. Use a separate sheet for each change in fuel, ignitor type, or ignitor location.

Fuel Spray Ignition Tests

The fuel spray ignition tests will be conducted with the BRL fuel spray device (an electrically primed caliber .50 cartridge case with holder, timer, etc.). This device has been shown to produce a fuel spray which closely approximates, in quantity, velocity, and dispersion, the spray resulting from caliber .50 bullet impacts on self-sealing fuel cells.

1. Caliber .50 cartridge cases are to be cleaned inside and outside prior to use. The mouths of the cases are to be checked for smoothness and roundness prior to use.

2. Electric primers are to be carefully pressed into the cases after used primers have been removed.

3. Cases are to be filled to the brim with fuel and covered with a small piece of tissue paper to retain the fuel in the firing position. Care should be taken so that no air is trapped in the cartridge cases.

4. The spray device is to be fired horizontally and the emerging spray ignited by the ignition sources of interest. Particular emphasis will be placed upon the ignition of the spray pattern produced in the first 18 inches beyond the mouth of the nozzle.

5. Still pictures of the test equipment will be taken prior to the start of the tests.

6. High-speed motion picture documentation will be taken for each fuel and type of ignition source.

7. The ignitor variation will be performed in the following way:

   a. First, tests are to be run using JP-4 with the electric spark ignition source. (This will be a continuous AC spark.)

   b. From an analysis of the fuel spray dispersion test data, determine a Y-distance from the axis of the fuel spray where an ignition is probable at X-distances of 6 and 18 inches (see data sheet). Place the ignitor at the selected Y-distance and 6-inch X-distance.

   c. Fire the fuel nozzle and observe the results.

   d. If an ignition occurs, move the ignitor out 2 inches and repeat the test.

   e. If no ignition occurs on the first test, complete three tests at this location.

   f. If the three tests produce two ignitions, move the ignitor out an additional 2 inches. If less than two ignitions are produced, complete five tests at this point.

   g. If the five tests show less than 50 percent ignitions, this will be established as the ignition limit for the test condition. If more than 50 percent ignitions are achieved, again move out 2 inches and repeat five tests.

   h. Repeat a through g at the 18-inch X-distance.

   i. Repeat a through h with JP-4 and the hot metal surface ignition source.

   j. Repeat a through h with JP-4 and the friction spark ignition source.

   k. Repeat all tests (a through j) with the MEF emulsion.

   l. Repeat all tests (a through j) with the EF4-104 emulsion.

m. NOTE: While the electric spark ignition source is essentially a point source, the hot surface and friction spark ignitors will be more nearly line or plane sources. The line or plane will be oriented in a plane which is perpendicular to the spray axis so that the Y-distance from the closest point on the ignitor to the jet axis is clearly known and not confused by the dimensions of the source itself.

n. Record all test data which is pertinent on the attached data form. Use a separate sheet for each change in fuel, ignitor type, or ignitor location. Indicate the location, orientation, and size of the ignitor on the diagram.

Ballistic Impact Ignition Tests

The purpose of these tests is to evaluate the influence of fuel type upon the ignition of fuel spray produced by well-functioned incendiary ammunition impacts on several types of fuel cell material which may be used to contain future aircraft fuels.

The tests are to be conducted in the following manner:

1. Incendiary ammunition is to be used in these tests. Caliber .30 API, caliber .50 API or incendiary, and 20 mm API rounds are to be used.

2. Ammunition will be used at service velocity and a range of approximately 100 feet for all tests.

3. Test fuel cell panels will be clamped to the test tank between flanges.

4. The test tank will be 14 inches inside diameter and 30 inches long and will provide for test panels on the impact and exit surfaces. If tests indicate that the rigid tank imposes too much load on the panels, a flexible tank will be used with 20 mm tests.

5. Test tanks will be filled to approximately 80 percent of capacity with the fuel to be tested.

6. All ballistic impacts are to be below the liquid level and at about 1/2 the fuel depth.

7. High-speed motion picture documentation is to be used with each test. The ignition of fuel spray from the front surface is of primary importance.

   Still photographs of resulting fires or of fuel leakage will be taken <u>before</u> panels are removed from the test tank. These pictures will be taken as soon as practical after bullet impact.

8. Aluminum function plates will be placed in the line of fire and in front of the test tank to insure a well-functioned incendiary burst in the space where the fuel spray is expelled from the front surface of the tank.

9. The following tests are to be performed:

Ammunition	Fuel	Tank Material
Cal. 30 API M-14	JP-4	Conventional self-seal
"	"	Crash resistant
"	"	New self-seal
"	MEF	Conventional self-seal
"	"	Crash resistant
"	"	New self-seal
"	EF4-104	Conventional self-seal
"	"	Crash resistant
"	"	New self-seal
"	WSX-7165	Conventional self-seal
"	"	Crash resistant
"	"	New self-seal
Cal. 50 API M-8	JP-4	Conventional self-seal
"	"	Crash resistant
"	"	New self-seal
"	MEF	Conventional self-seal

Ammunition	Fuel	Tank Material
Cal. 50 API M-8	MEF	Crash resistant
"	"	New self-seal
"	EF4-104	Conventional self-seal
"	"	Crash resistant
"	"	New self-seal
"	WSX-7165	Conventional self-seal
"	"	Crash resistant
"	"	New self-seal

10. The following data items will be recorded for each test:

a. run number
b. date
c. ammunition caliber and type
d. fuel type
e. fuel cell material used
f. camera framing rate
g. camera f stop
h. camera lens used
i. lighting conditions
j. film type
k. planned time interval between camera start and power to firing circuit
l. ambient conditions, temperature, wind, etc.
m. comments regarding results
n. name of person responsible for data recorded.

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13. ABSTRACT

This evaluation of emulsified JP-4 has concentrated upon the fuel properties which relate to the ignition and propagation of fire under the conditions of ballistic attack and survivable aircraft accidents. The specific areas of study and testing include the following: (1) fuel combustion rates as a function of air velocity and air temperature, (2) fuel vaporization rates under closed-tank and vented-tank conditions, (3) fuel permeability, (4) fuel dispersion characteristics under conditions of high-velocity ballistic impact and spillage from heights to 20 feet, (5) ease of fuel droplet or spray ignition with various energy sources, (6) fuel and tank panel behavior when hit by functioned incendiary bullets, (7) fire extinguishing ease with a variety of extinguishants against a standardized fire, and (8) self-sealing panel performance with fuel emulsions. It has been concluded from this study that emulsified fuels offer opportunities for greater aircraft survivability from several standpoints. They may be employed most advantageously as a part of a total passive defense system for aircraft fuel.

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14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
aircraft vulnerability						
crash fires						
combat fires						
emulsified fuels						
JP-4						
small arms ammunition						
burning rate						
vaporization rate						
fuel explosions						
fuel dispersion						
fuel ignition						
incendiary ammunition						
self-sealing fuel tanks						
crash-resistant fuel tanks						
fire extinguishing tests						

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